D K Mak

ASSESSMENT OF THE NON-DESTRUCTIVE TECHNOLOGY REQUIRED FOR INSPECTING OFFSHORE STRUCTURES

FINAL REPORT
BY
Det norske Veritas (Canada) Ltd.

Work on this project was conducted under the auspices of
Physical Metallurgy Research Laboratories
Canada Centre for Mineral and Energy Technology
Energy, Mines and Resources Canada

DSS FILE NUMBER : 15SQ.23440-2-9108
DSS CONTRACT SERIAL NUMBER : OSQ83-00035
CANMET PROJECT NUMBER : 23440-2-9108
CANMET SCIENTIFIC AUTHORITY : Dr. D. Mak

188 p.p
+153 pp

MICROMEDIA

March 1984

This report should be cited by D.S.S.
File No. 15SQ.23440-2-9108

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TECHNICAL REPORT

Date	13.03.84
VERITAS Report No.	84-CGY-015
Subject Group	E8
Department	Offshore
Project No.	04.D.100
Title of Report	Assessment of the Non-Destructive Technology Required for Inspecting Offshore Structures
Approved by	J.E. Hagen Hagen
Client/Sponsor of project	Energy, Mines & Resources Canada Canada Centre for Mineral & Energy Technology
Client/Sponsor ref.	Dr. D.Mak
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Summary

This report contains a critical review and assessment of the methods used for non-destructive evaluation (NDE) of offshore structures. Both conventional techniques and methods under development have been addressed, and the capabilities of Canadian and foreign organizations to perform offshore inspection have been evaluated. A comprehensive literature search has been conducted for this study and attempts were made to enlighten the review by the experience of offshore inspectors. Leading NDE companies and research establishments were visited for direct evaluation. The report also contains a review of the NDE equipment together with their specifications & manufacturing. Recommendations on the transfer of NDE technology to Canada and future development in this field have been proposed.

4 Indexing terms
Non-Destructive Tests
In-service Inspection
Offshore Structures
Underwater Inspection

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Date of last rev.	31.01.84
Rev. No.	1
Number of pag	180

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1. INTRODUCTION

1.1 Objectives and Scope

The study reported herein was commissioned by Canada Centre for Mineral and Energy Technology (CANMET) to:

- evaluate the current state-of-the-art in non-destructive evaluation (NDE) techniques for the inspection of offshore structures;
- evaluate the capabilities of Canadian and foreign inspection organizations for offshore work;
- propose recommendations for future development work on the most promising NDE methods and equipment.

Both the currently used and prospective NDE techniques have been reviewed. The currently deployed NDE methods used in offshore inspection that are addressed in the report are:

- visual inspection by divers and remotely operated vehicles (ROV);
- methods based on electromagnetism such as magnetic inspection, megnetography and the eddy current technique;
- AC potential drop measurement;
- ultrasonic testing;
- radiographic testing.

The following prospective NDE methods have also been assessed:

- acoustical holography;
- ultrasonic tomography.

The principal components of equipment for each method have also been described and their specifications given.

The assessment of inspection methods used for the NDE of offshore structures was based on such criteria as cost-effectiveness, quality, reliability and applicability as to water depth.

1.2 Methodology

Detailed information on various NDE techniques and equipment that are currently available or are being developed were obtained as follows:

- survey of NDE organizations, supplying services and equipment, by questionnaire;
- survey of NDE organizations by visit and interview;
- literature search.

Leading companies and research organizations in Europe, North America and Japan were covered by the survey. A list of the organizations contacted and visited is in Appendix A, and the questionnaire is in Appendix B.

The response to the questionnaire was somewhat unsatisfactory. However where information was not available directly, efforts were made to obtain this indirectly so that no significant data sould be omitted.

VERITAS' longstanding involvement in the survey of offshore structures has resulted in the establishment of a unique data bank, enlightened by the experience accumulated over many years. The study has benefitted considerably from this.

The information collected was critiqued and assessed on the basis of criteria developed in the light of experience gained from the inspection of structures in various offshore locations.

1.3 Non-destructive Evaluation of Offshore Structures - An Overview

"Non-destructive evaluation" of an offshore structure, or components thereof, is defined here as the process whereby the locations and characteristics of material flaws in the structure can be determined without imparing the functional capability of the structure or its components.

NDE is used for inspection during fabrication and when the structure is in service. This study pertains mainly to the in-service inspection of offshore structures.

The objective of in-service inspection is to ensure that the structure remains safe during its lifetime and that any defect or damage is detected in time for appropriate remedial measures to be taken to preserve the integrity of the structure.

Offshore inspection differs from inspection of other types of installations in respect of the following:

- limited accessibility (sea storms, aqueous environment, marine growth, etc.);
- hazardous areas;
- new and untested designs;
- large structures;
- consequences of failure (e.g. riser rupture within the concrete shaft);
- high costs (production loss, inspection by divers, ROV's, etc.);
- deterioration processes dependent on environment;
- limited space on board of installations.

The most problematic aspects of the NDE of offshore structures arise from the need to carry out inspection underwater.

Underwater inspection has been categorized into the following types:

Type I	General visual inspection (no cleaning) referred to as the green survey.
Type II	Close visual inspection (cleaning generally required) referred to as the blue survey.
Type III	Inspection using the non-destructive testing, referred to as the red survey.

When using NDE techniques for the Type III inspection, the principal concern is finding crack-like (planar) defects. The cracks may have developed as fatigue cracks, corrosion fatigue cracks, stress corrosion cracks, hydrogen induced cracks, lamellar tear cracks, etc. In most cases these cracks develop in areas of high stress concentrations from initial fabrication defects induced, especially in welds, during fabrication, transport and assembly of the structure.

The in-service inspection of offshore structures does not duplicate the NDE inspection at the fabrication stage. The goal of underwater NDE inspection is not therefore to look for common defects in welded joints such as porosity, lack of fusion, lack of penetration, undercuts, underfills, etc.; rather, it is to detect surface breaking cracks which may have been identified during Type I and Type II inspection. For example, according to the UK guidelines for inservice inspection, 10% of all welds should be inspected for cracks every five years. Using probabilistic analysis it was found[1.1*] that an evaluation of a 10% random sample of all welds results in the same probability of finding a crack as if evaluating 10% sample taken from the fifty highest stressed welds. It is of importance therefore, to properly identify the "critical zones" on the structure when planning an inspection program.

Current rules, regulations and guidelines mainly cover inservice inspection of the primary and secondary structure of offshore installations[1.2-1.6]. Fig. 1.1 shows a comparison between British, Dutch and Norwegian requirements to underwater inspection of steel structures. Rotational inspection tends to be the technique currently used for most offshore structures.

Offshore regulations require periodic inspection annually, biannually and 5-yearly, the latter to be spread out as annual/biannual inspection. In addition, special inspection is required in connection with damage or suspected damage and repair. Norwegian Petroleum Directorate (NPD) may also require two additional inspections, namely "initial inspection" after installation and "start-up inspection". The latter is in particular used for pipeline/riser start-up.

---

[*] Numerical superscripts identify references listed in Chapter 9.

FIGURE 1.1

STEEL STRUCTURES UNDERWATER INSPECTION

	GB			NL			N
							NPD
	ANNUAL	BIANNUAL	5-YEARLY	ANNUAL	BIANNUAL	5-YEARLY	ROTATIONAL
MECHANICAL DAMAGE		X	X	X			X
GENERAL CORROSION/PITTINGS		X	X	X			X
MARINE GROWTH		X	X	X			X
SCOUR, DEBRIS		X	X	X			X
INSPECTION OF ANODES		X	X	X			X
POTENSIAL READINGS			X		X		X
CLOSE VISUAL INSPECTION			X			X	X
INSPECTION OF REPAIRS	X		X	X			X
NON-DESTRUCTIVE TESTING			X		X	X	X
THICKNESS MEASUREMENTS			X		X	X	X

A 4-5 year program is set up for the assessment of long-term integrity. This program is then generally spread over the whole operation period and thus becomes a part of the periodic annual/biannual program; it consists of two parts, a mandatory inspection for short term safety and a long term inspection.

For each installation the annual program is normally specified in inspection guidelines. In addition to a general part, they usually contain the following:

- type of inspection;
- extent of inspection;
- procedures;
- equipment;
- personnel.

There is clearly scope for the improvement of the presently available NDE techniques. The reliability of NDE methods are affected by such factors as environmental constraints, limited experience and training of the diving inspectors, stress and fatigue of the divers, inadequate equipment and procedures. The problems encountered range from the non-detection of a significant defect to the detection of a defect where none exists.

Available information on inspection reliabilities, which may be expressed in terms of the probability of detection and correct characterization is scarce and often qualitative in nature. This limits the ability to optimize inspection efforts at the present time. More work should be done in establishing reliability data for the NDE methods currently in use, or under development, for underwater inspection.

Generally cost-effective operations of offshore installations should incorporate a proper coordination of design and inspection planning. The total costs of design, production, operation, and inspection should be minimized taking into account the following factors related to inspection:

- determination of design-critical defect size;
- design for inspectability;

- planning of inspection;
- inspection operations;
- evaluation of results;
- acceptance criteria reflecting expected reliability.

It is hoped that the assessment contained in this report constitutes a contribution to defining the reliability of the available NDE techniques as well as identifying where future research and development in this field will be most beneficial.

2. CURRENT NDE TECHNIQUES FOR OFFSHORE INSPECTION

2.1 Inspection Methods

Methods currently used for underwater inspection include the following:

- visual inspection;
- methods based on electromagnetism;
- potential drop measurement;
- ultrasonic testing;
- radiography.

2.1.1 Visual Inspection

Visual examination is fundamental to virtually all in-service NDE performed on offshore structures. Visual inspection programs are structured to examine the general condition of the structure with the purpose of detecting obvious damage (type I survey), and then more closely examine areas of high stress concentration ("hot-spots") or previous damage (type II survey). The type II survey also requires the diver/inspector to check underwater structures for coating and corrosion damage, anode condition, marine growth, scouring and debris.

Depending upon the results of the type I and II visual examinations, detailed, instrument-assisted, type III examinations (described in subsequent sections) may be required. Regulatory requirements and the operators' program also require that certain node joints, key welds and other "hot spots" be given a type III survey on a periodic basis; type III surveys are considered to be beyond the realm of visual inspection alone.

In most situations visual examination is affected by water clarity and illumination. In addition, physiological and psychological problems which increase with depth limit the efficiency and ultimate capability of divers. Hence, the use of remotely operated vehicles (ROVs), manned submersibles and atmospheric diving suits is rapidly evolving for visual examination, repair and maintenance work.

Reporting is the most important part of visual examination. When using an improperly qualified diving inspector, irrelevant findings are often reported while significant defects may be left unreported. Application of other (instrumented) NDE techniques depends to a large extent on results of the visual inspection.

2.1.2 Methods Based on Electromagnetism

Surface breaking defects in ferromagnetic materials cause local changes in magnetic permeability hence, when a magnetic field is induced in the material, magnetic flux leakages will occur at the defects. The flux leakages can be detected in a number of ways thereby delineating the defects. Three methods based on electromagnetic principles are often used for underwater applications:

- magnetic particle inspection (MPI);
- magnetography;
- eddy current method.

2.1.2.1 Magnetic Particle Inspection (MPI)

Magnetic particle inspection is the most commonly used technique for detailed examination of offshore structures for stress cracks. Its purpose is to enhance the appearance of cracks for ease of visual detection, thus providing a means for type III visual examinations. In principle, MPI performed underwater does not differ from above water wet magnetic particle testing which is described in detail in BS6072 (Method for Magnetic particle flaw detection), ASTM SE-138 (Standard Method for Wet Magnetic Particle Inspection), and other literature[2.1, 2.2].

2.1.2.1.1 Principle of MPI

The basic technique for MPI consists of evenly flooding the area of concern with a brightly coloured or fluorescent ink containing tiny magnetic particles. By temporarily magnetizing the area under examination, the magnetic particles will migrate to any surface-breaking cracks in that area. With the aid of bright or ultraviolet (in the case of fluorescent inks) light, the diver is then able to discern the cracks (Fig. 2.1).

Two major factors influence the effectiveness of MPI:

- orientation between the magnetic field and the defect;
- strength of the magnetic field.

2.1.2.1.2 Magnetization Methods

Ferromagnetic materials can be magnetized in two ways:

1. Direct magnetization. A magnetic field is induced in the material by an electric current passing through it using magnetization prods, Fig. 2.2. AC current of 2.5-4.0 A/mm r.m.s. will generate the necessary tangential peak field strength. The tips of the prods are fitted with special material (either a special lead or other low melting alloy) to avoid local heating and burn marks at the test surface.

   Recommended prod spacing is from 150-300mm while prod operation should be 20-30 degrees from the direction of the weld bead. Spacing between successive tests should be 40-50mm (Fig. 2.3).

2. Indirect magnetization. Magnetism is induced by placing the material in a strong magnetic field which can be generated by:

   - a magnetization coil which should be placed 50-100 mm outside the test area. Surface cracks parallel to the coil will be detectable;

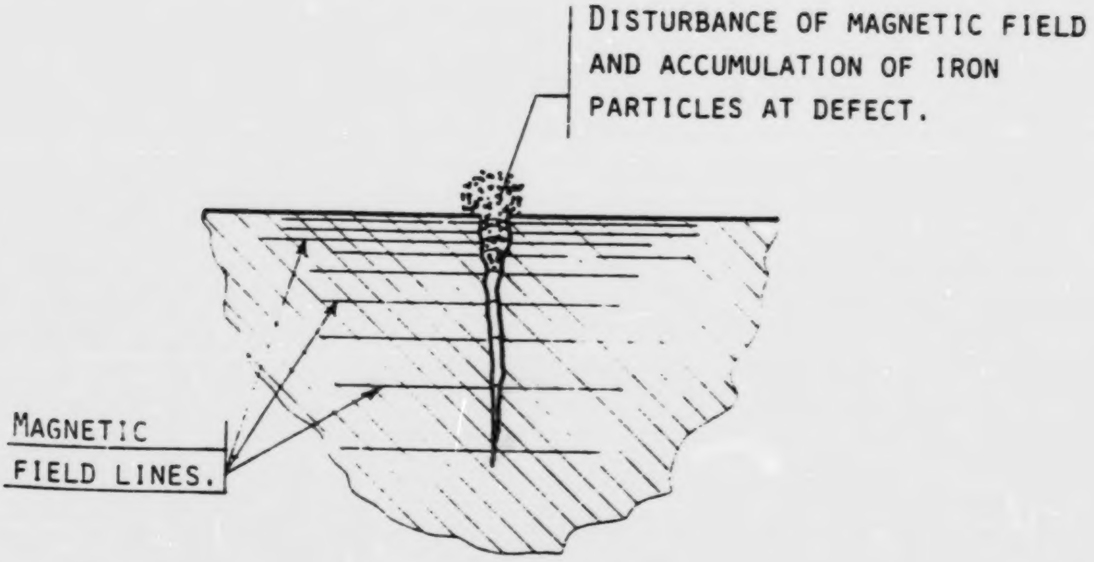

DISTURBANCE OF MAGNETIC FIELD AND ACCUMULATION OF IRON PARTICLES AT DEFECT.
MAGNETIC FIELD LINES.

Figure 2.1 Delineation of Defects by Magnetic Particles [2.3]

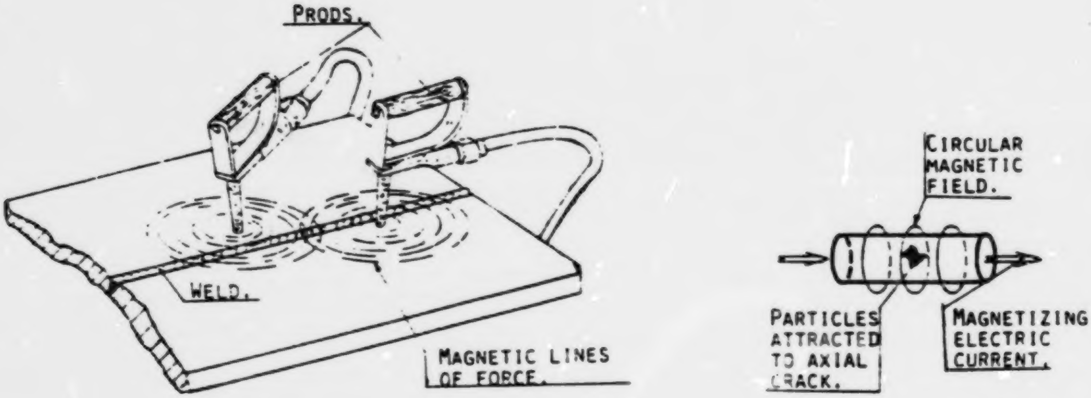

PRODS.
WELD.
MAGNETIC LINES OF FORCE.
CIRCULAR MAGNETIC FIELD.
PARTICLES ATTRACTED TO AXIAL CRACK.
MAGNETIZING ELECTRIC CURRENT.

Figure 2.2 Direct Magnetization [2.3]

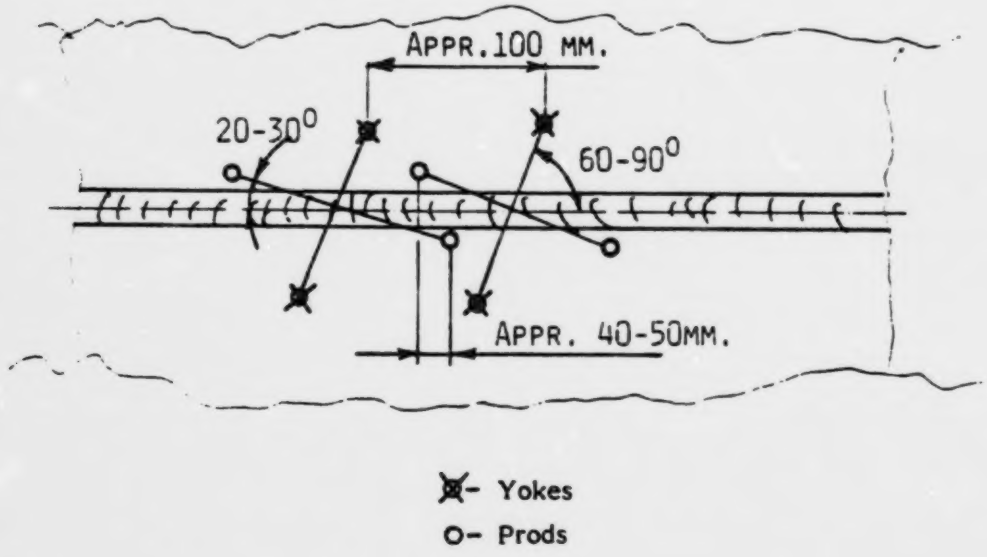

APPR.100 MM.
20-30°
60-90°
APPR. 40-50MM.
- Yokes
O- Prods

Figure 2.3 Optimal Prod or Yoke Positions [2.3]

- a parallel conductor. Cracks running parallel to the conducter in the area between the loop can be detected;

- an AC electromagnetic yoke which generates a longitudinal magnetic field, Fig. 2.4;

- a permanent magnet yoke which is similar to the AC electromagnetic yoke except that the field strength is not adjustable and may be of limited strength.

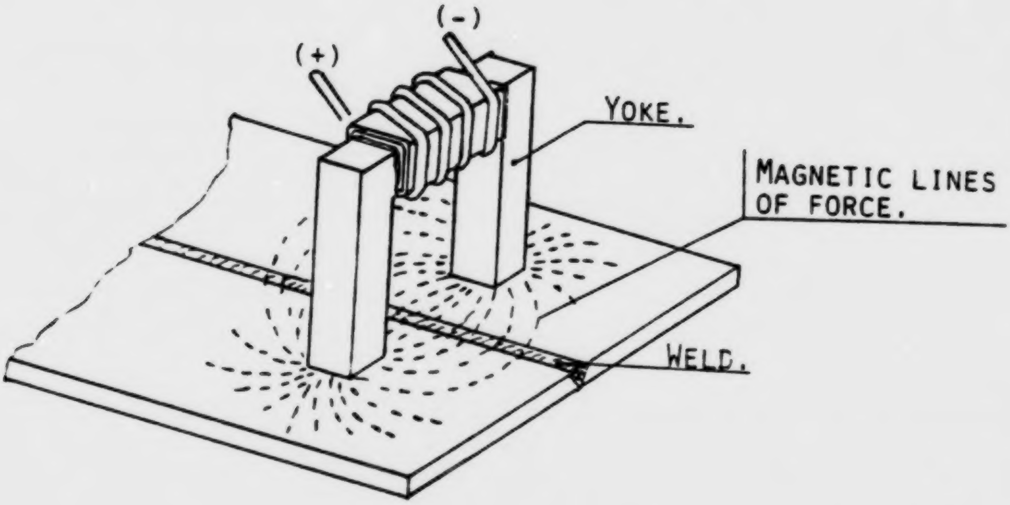
  Yokes should be oriented at an angle of 60-90 degrees from the direction of the weld as shown in Fig. 2.3.

2.1.2.1.3 Magnetic Field Strength

If the magnetic field is too weak, the magnitued of flux leakage at discontinuities will be insufficient for magnetic particle migration. Similarly, if the field is too strong (approaching magnetic saturation) differences between the overall field strength and flux leakage locations will be insufficient to cause particle movement. In either case detectability will be adversely effected.

Magnetic field strength should be verified with a hall probe or similar instrument. This especially applies to complex surface geometries such as node welds. Field strength may be verified above water by using models with the same geometries and materials as the objects to be examined.

All electromagnetization should be done with alternating or half wave rectified current which should be measured as an r.m.s. value.


(-)
(+)
YOKE.
MAGNETIC LINES OF FORCE.
WELD.

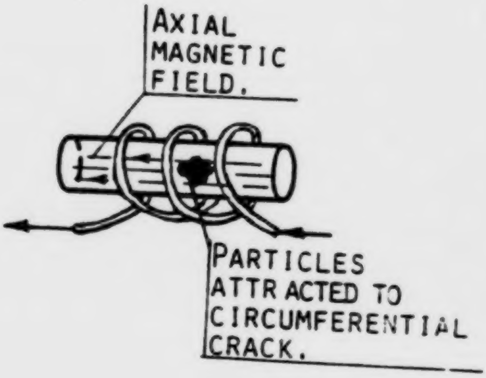

AXIAL MAGNETIC FIELD.
PARTICLES ATTRACTED TO CIRCUMFERENTIAL CRACK.

Figure 2.4 Indirect Magnetization [2.3]

2.1.2.1.4 Documentation of MPI Results

When using fluorescent or non-fluorescent magnetic particles, still photography or video should be used to document examination results and actual magnetization setup. However another technique, the Magfoil Method, has been developed and provides immediate documentation of test results[2.4]. Magfoils contain magnetizable particles which are held with other substances in a flat, hose-type container made of flexible foil. In addition, a mixture of fluids is contained in another partition of the Magfoil. To use the Magfoil, the operator applies pressure to the partition containing the fluids. After the partition breaks, the particles and fluids are mixed, the Magfoil is pressed to the surface over the defect area and is then magnetized for up to 2 minutes. Once the magnetic particles have accumulated over the flaw and the fluids have hardened these particles into position, the Magfoil can be removed for evaluation purposes.

2.1.2.2 Magnetography

Magnetography was developed and patented by Magnetische Pruefanlagen GmbH, Reutlingen, West Germany under the commercial name Magneto Marine Method.

The physical principle of the magnetographic method is similar to MPI in that it also utilizes flux leakage as a means of identifying discontinuities. Magnetography does not use accumulation of magnetic particles for defect delineation, rather the disturbed magnetic field is directly stored on a flexible magnetic tape which is stretched over the weld area to be inspected[2.5]. In typical underwater applications, a weld length of about 0.5m is inspected in one procedure. A short magnetizing pulse of about 15ms duration, fed from a battery-supplied capacitor into a yoke, magnetizes the weld area over the yoke length and records the stray flux caused by the surface breaking cracks onto the tape. The tape is then taken to the surface where it is processed, the signals displayed on an oscilloscope or reproduced on a strip chart (C-scan record) and the results interpreted by a qualified technician.

2.1.2.3 Eddy Current Method

Eddy current testing is an NDE method based on the principle of electromagnetic induction and was originally developed for continuous testing of tubular products. The test is performed by passing the tube through or near a coil energized with alternating current. The presence of the tube modifies the impedance of the coil which varies according to several paramters: the distance between the coil and the tube, dimensions of the tube, electrical coductivity, and magnetic permeability of the tube. The impedance changes caused by localized differences (material defects) in the tube then produce electrical signals which are amplified and modified to give the required defect indication (mechanical, digital, etc.).

Applying this principle for underwater applications, Thorburn Technics International (TTI) Ltd., Glasgow, Scotland, recently developed the Electro-Magnetic Detection (EMD) technique. Using EMD, signals are processed using a balanced AC bridge detector system, making it possible to examine undressed (rough) welds.

2.1.3 AC Potential Drop (ACPD) Measurement

The AC potential drop technique developed as a tool for measuring the depth of surface-breaking cracks identified visually through MPI. Although the principle of the method was well known[2.6], DnV further developed this technique with the necessary instrumentation for underwater use.

2.1.3.1 Principle of ACPD

The method is based on the principle that a skin effect limits A.C. current to a very thin surface layer in metals. When a surface breaking crack is encountered the current is forced down into the material and around the crack ends (Fig. 2.5). Thus, when electrical field density is measured between two contacts placed on the surface of a test piece, the measured potential across a crack will increase with crack depth because the surface current path and hence effective resistance increases.

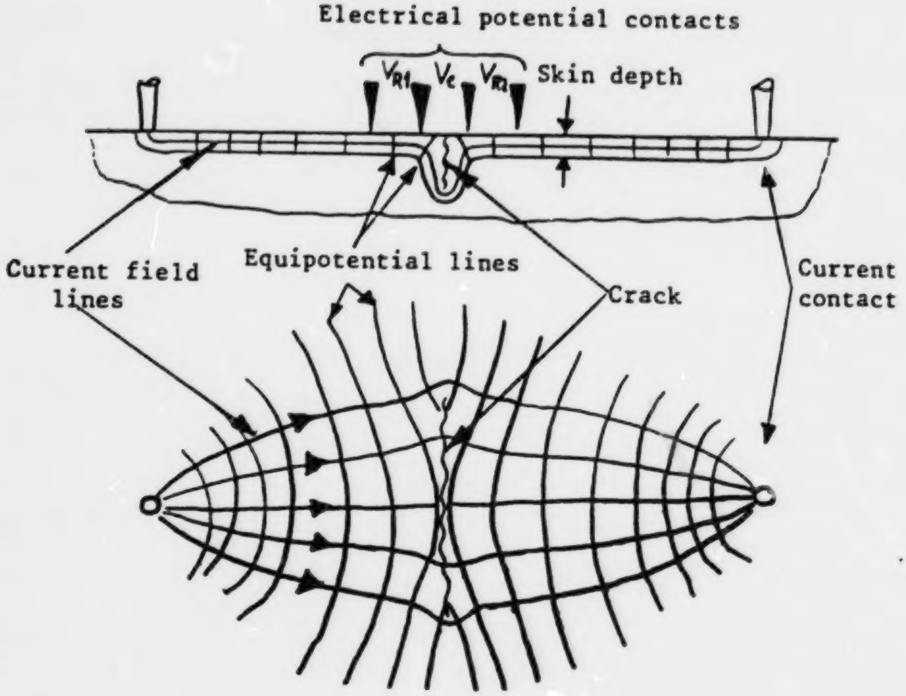

Electrical potential contacts
V_{R1}
V_c
V_{R2}
Skin depth
Current field lines
Equipotential lines
Crack
Current contact

Figure 2.5 A C Field Distribution Around a Surface Breaking Crack 2.7

2.1.4 Ultrasonic Testing (UT)

2.1.4.1 Principle of UT

When testing materials with ultrasonic waves, high-frequency sound waves propagage in solid bodies as directed beams, with very little attenuation. If the material is homogeneous the velocity of the propagating waves is constant. Hence, by measuring the time it takes for the wave to travel through the material, its thickness can be determined. In addition, at interfaces between media with different acoustic properties, such as air and metal, the waves are almost completely reflected. This makes it possible to detect cracks, inclusions and other flaws by means of ultrasonic waves.

To generate sound waves, an electric pulse is generated in the test instrument and transmitted to a transducer (transmitter) which converts the electric pulse into mechanical vibrations. These vibrations are transmitted into the object being tested where they are scattered, attenuated, reflected and resonated. A portion of this energy returns to the transducer (receiver) where it is reconverted to the electrical energy and transmitted to the test instrument where it is amplified and displayed, either digitally or on a cathode ray tube (A-scan).

For the testing of materials, piezo-electric crystals (commonly quartz or barium titanate) formed as thin plates are used for generating ultrasonic waves. If an alternating voltage is applied to the electrodes, the plate will vibrate with the frequency of this voltage, i.e. the transducer emits sound waves. Conversely, a sound wave striking the transducer produces a voltage at its electrodes.

2.1.4.2 Basic UT Methods

Ultrasonic testing of materials may be performed using the following basic methods:

- the reflection (pulse-echo) method;
- the transmission method;
- the immersion method.

Reflection (pulse-echo) Method

When an ultrasonic pulse is transmitted to the object, the time delay between the initial pulse and the echo from the back surface, or from a flaw inside the object, is measured (Fig. 2.6). Using this method, the thickness of the material and location of any flaws can be located exactly from one side of the object.

Transmission Method

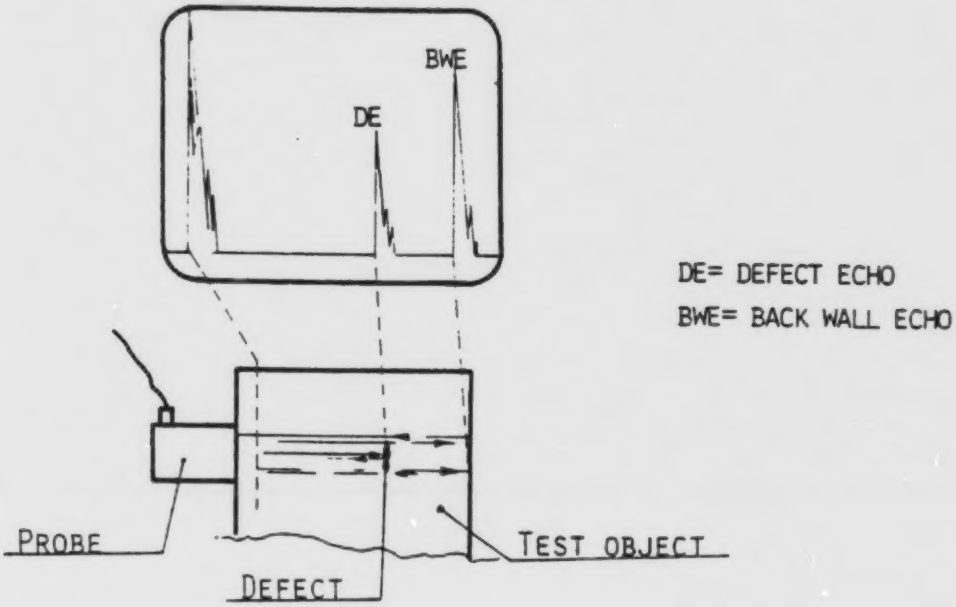
Using the transmission method (Fig. 2.7), a pulse generated on one side of the test piece is received on the other side. (Access to both sides of the specimen is therefore required). The time-delay between signal transmission and reception is then measured. Defects are subsequently detected because of a decrease in signal strength, appearing as a reduction in echo height.

Immersion Method

One disadvantage of applying the transducer directly to the surface of the test piece is that the transmitted pulse tends to mask out those echos which arrive during or immediately after the transmission phase. Hence, information about near surface discontinuities is lost in the "near-field dead-zone". The immersion method (Fig. 2.8) has the advantage that the near-field dead-zone will occur in the water. Therefore defects located closer to the surface of the object can be detected more easily by this method when compared with the conventional pulse-echo method.

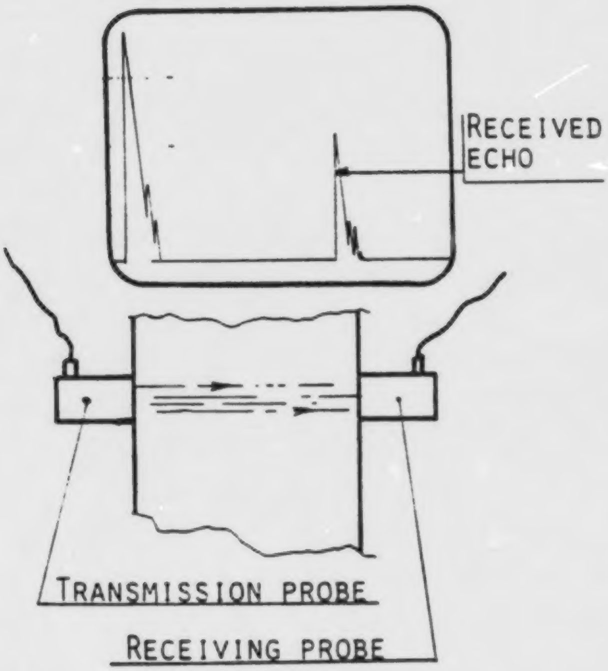
2.1.4.3 P-scan UT

The new P-scan technique (Projection image Scanning technique) developed by the Danish Welding Institute represents a remarkable step forward towards a more reliable, more operator independent and more reproduceable ultrasonic inspection of welds.



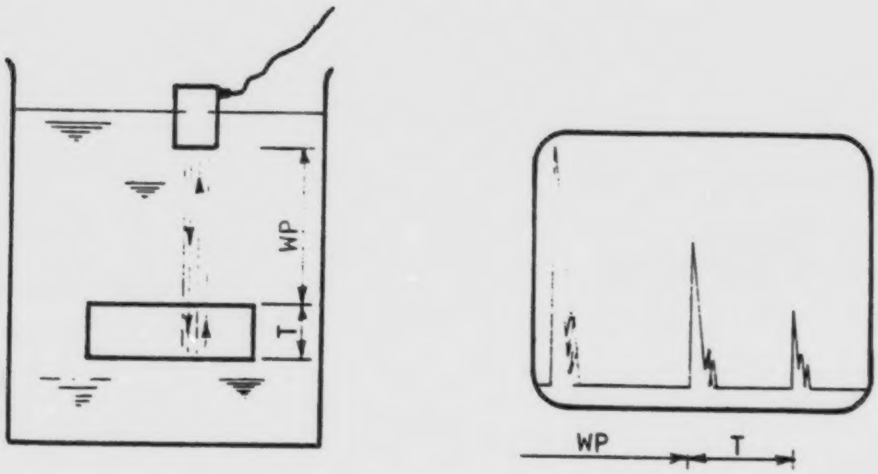
BWE
DE
DE= DEFECT ECHO
BWE= BACK WALL ECHO
PROBE
TEST OBJECT
DEFECT

Figure 2.6 The Pulse-Echo Principle 2.3



RECEIVED ECHO
TRANSMISSION PROBE
RECEIVING PROBE

Figure 2.7 The Transmission Method 2.3



WP= WATERPATH

Figure 2.8 The Immersion Method 2.3

In the P-scan technique, echoes from weld defects are measured with one dB resolution and recorded together with the corresponding defect positions. Defect positions are then visualized as a projection of the defects on one or more projection planes. Usually two projection planes are used: one parallel to the surface and another plane normal to the surface parallel to the weld. Thus, defects appear as a top view and a side view. By using two projection planes, a complete three dimensional location of weld defects is obtained. In addition, all the maximum echo amplitudes along the weld are displayed in a logarithmic scale.

2.1.4.4 Probes

When testing materials with ultrasound, three types of probes can be used: the normal probe (longitudinal waves); the angle probe (transverse waves); and the double crystal probe.

Normal probe

A normal probe generates longitudinal waves and transmits them (via a couplant such as oil, grease or water) into a test object in a direction normal to the plane of the surface to which the probe is applied. The pulse propagates in a straight direction, but owing to beamspread, the sound field from the probe will become cone-shaped. The angle of beamspread is related to probe diameter and frequency. Using normal probes, Figure 2.9 illustrates how the multiple-echo technique may be used to measure material thickness. Note also that the echo height on the screen decreases as the length of the sound path increases.

A method which is suitable for sizing large defects with normal probes is the 6 dB-drop method, also called the half-value-method, Fig. 2.10. When a defect is detected, the probe is moved towards the edge of the defect until the defect echo height is reduced by 6 dB (or 50%), and the center of the probe is marked as the edge of the defect. By moving the probe around the defect in this fashion, the extent can be plotted. The same technique can be used with angle probes described below.

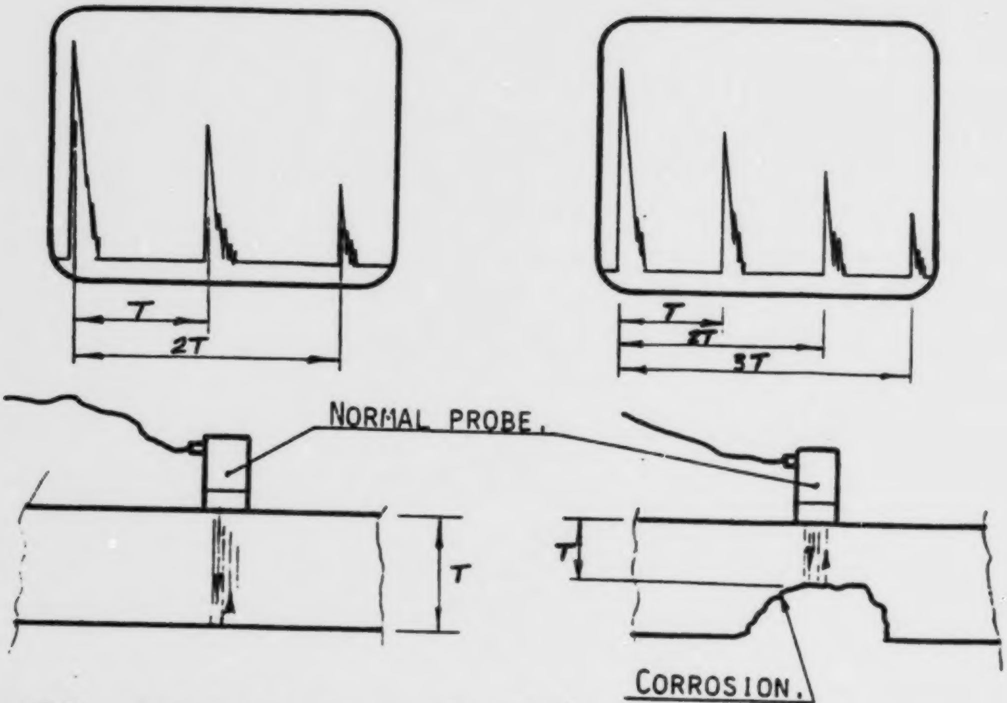

T
2T
T
2T
3T
NORMAL PROBE.
T
T
CORROSION.

Figure 2.9 Application of a Normal Probe 2.3

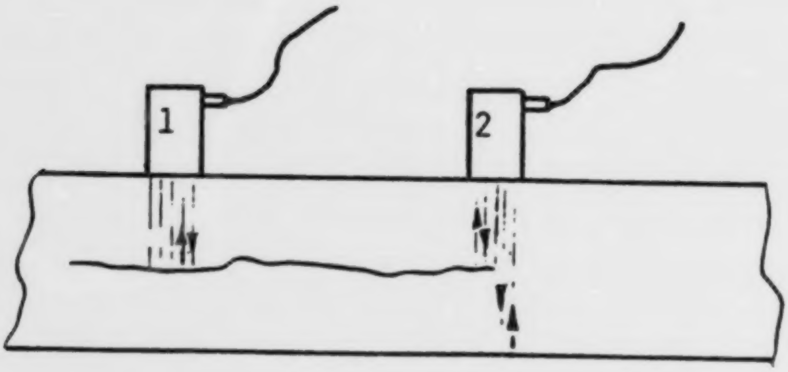


Figure 2.10 Determination of Flaw Size 2.3

Angle probe

An angle probe consists of a longitudinal wave element cemented to a wedge of plastic (perspex etc.) at an angle, see Fig. 2.11. If the wedge is applied to a material via a couplant, the wave will be refracted into the material at an angle. The refracted wave is a shear (transverse) wave and commercial shear wave probes are usually marked with the angle of shear wave in steel. Table 2.1 gives the angles of refraction in different materials for angle probes having an angle of incidence of 35-80 degrees with respect to steel. The sound field from the probe will appear cone-shaped as for the normal probe and the angle of beam spread can be calculated when the dimensions of the piezo-electric element and the frequency are known.

Double crystal probe

A double crystal probe (Fig. 2.12) consists of two separated piezo-electric elements (a transmitter and a receiver) at an angle (1 degree - 5 degrees) to the normal. The elements are cemented to plastic blocks (perspex etc.) and separated by cork insulation. Since the initial pulse must pass the acoustic delay block before reaching the contact surface of the material, it will not interfere with defects immediately below the contact surface. Hence, the dead zone will be greatly reduced.

TABLE 2.1

BEAM ANGLES OF REFRACTION[2.3]
(in Degrees)

Steel	35	45	60	70	80
Aluminium	33	42.5	55.5	63.4	69.6
Copper	23.6	29.7	37.3	41	43.5
Cast Iron	23	28	35	39	41

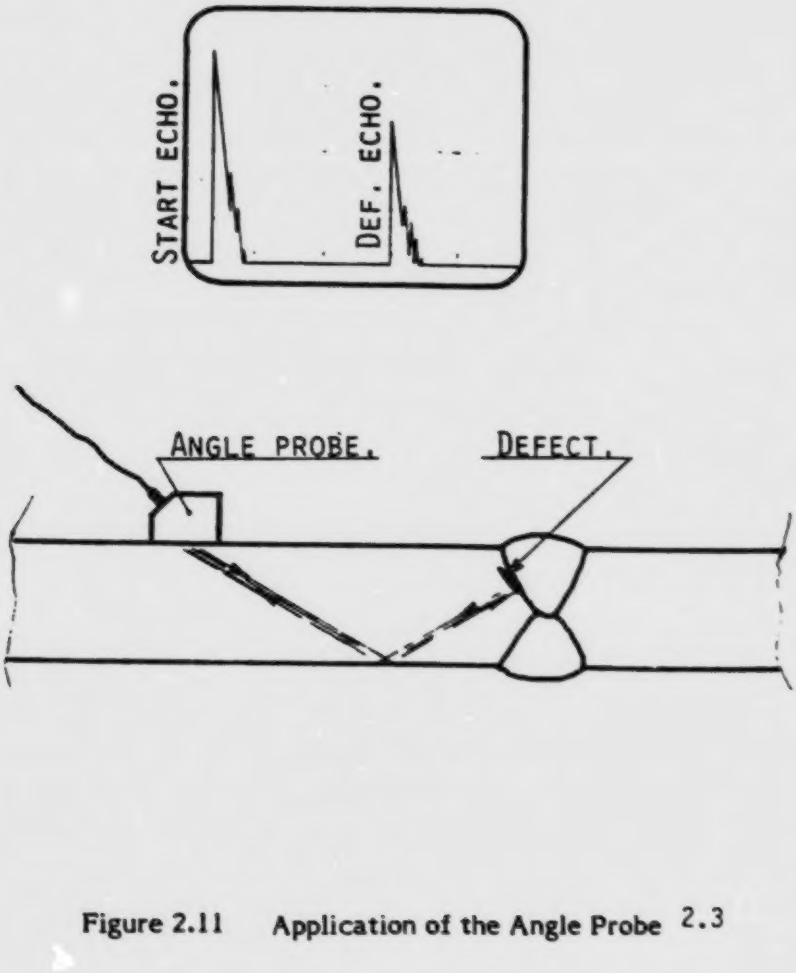

START ECHO.
DEF. ECHO.
ANGLE PROBE.
DEFECT.

Figure 2.11 Application of the Angle Probe 2.3

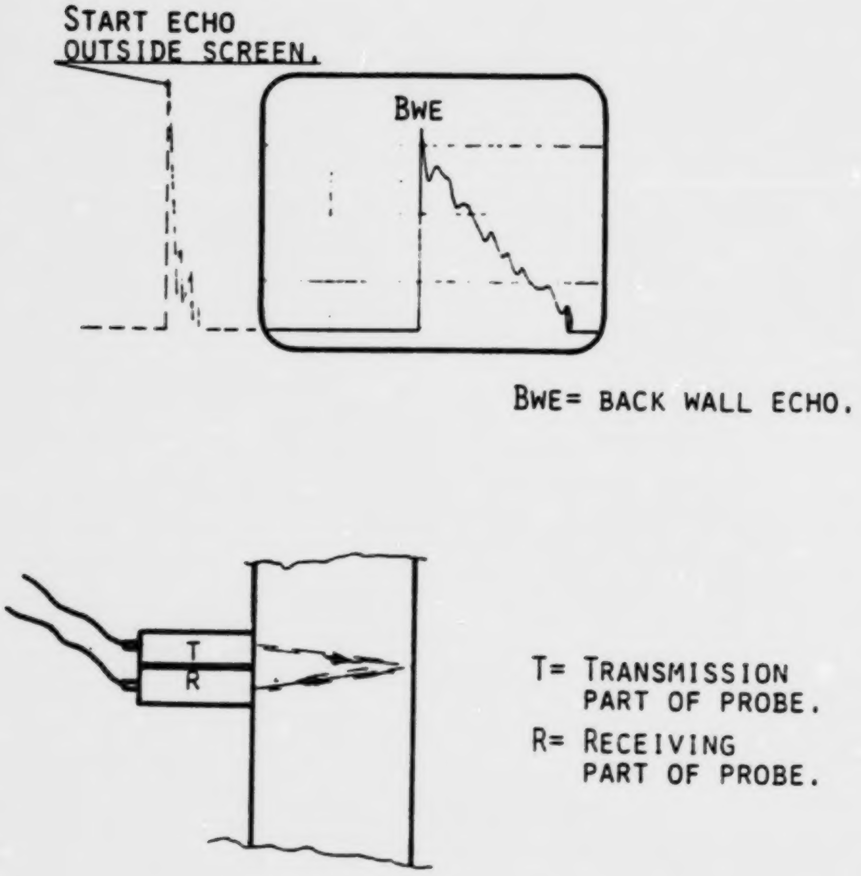

START ECHO
OUTSIDE SCREEN.
BWE
BWE= BACK WALL ECHO.
T
R
T= TRANSMISSION
PART OF PROBE.
R= RECEIVING
PART OF PROBE.

Figure 2.12 Principle of the Double Crystal Probe 2.3

An ultrasonic pulse from the transmitter element will propagate via the delay block into the material; reflected pulses from defects will reach the receiver element resulting in a defect echo on a CRT screen. The delay block and separate transmitter-receiver configuration, make the double crystal probe useful for detecting defects immediately below the contact surface and for measuring thicknesses within the range 1-30 mm.

With a double crystal probe, the first echo is always used for registration. This increases the detection efficiency close to the surface of the material and prevents multiple echoes from reaching the receiver.

2.1.5 Radiographic Testing (RT)

Radiography is an NDE technique used in examining volumetric (three-dimensional) weld defects such as pores, slag inclusions, slag lines, incomplete penetration, etc. For the underwater application, RT is typically used to test repaired welds and pipeline tie-in welds.

2.1.5.1 Principle of RT

Using RT, the image of the tested area, produced by the passage of a radiation beam through the test object is recorded on film for permanent documentation (Fig. 2.13). Thus, film interpretation is performed by a qualified NDE technician on the surface.

Radiographic testing can be performed using two types of radiation:

- x-rays, which are produced electrically by an electron beam in a high voltage electric tube;
- γ-rays, which are produced by the decay of radioactive material such as Cobalt 60 or Iridium 192. When applied below water, γ-ray equipment is preferred due to the hazardous high voltage of the x-ray source.

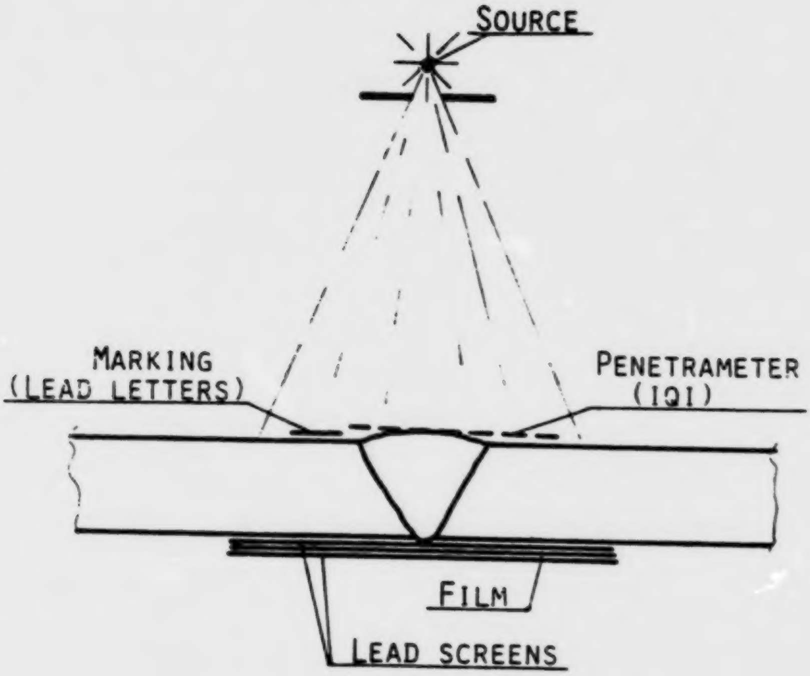

SOURCE
MARKING
(LEAD LETTERS)
PENETRAMETER
(IQI)
FILM
LEAD SCREENS

Figure 2.13 Radiographic Weld Examination 2.3

The penetrating power of radiation is a function of its energy. Depending on radiation energy, for example, radiographic testing can be used on material thicknesses equivalent to more than 100mm of steel. The energy of the radiation from radioactive isotopes is characteristic for each isotope and remains constant throughout the lifetime of the isotope. The energy of Iridium 192 radiation corresponds to an x-ray voltage of about 800 kV. For Cobalt 60 the corresponding x-ray voltage is approximately 3000 kV.

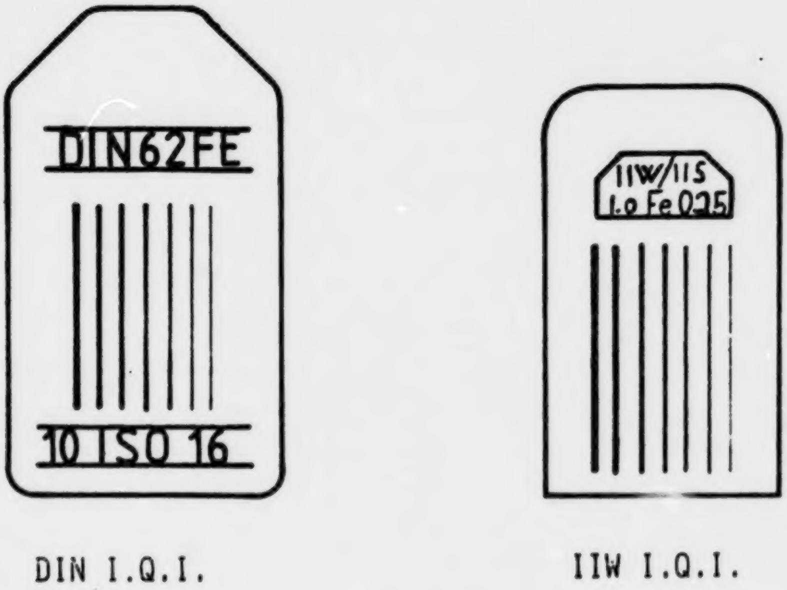
In order to determine the sensitivity of a radiograph, a penetrameter or image quality indicator (IQI) is used, Fig. 2.14, the most frequently used IQIs being ASME hole penetrameters.

2.2 Inspection Equipment

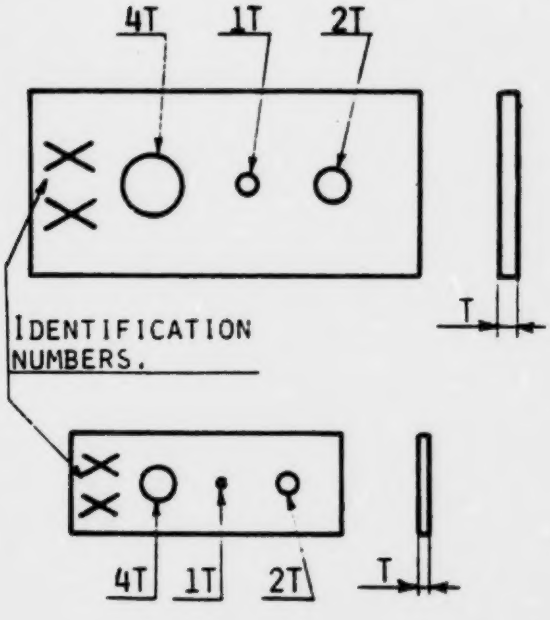
Descriptions and specifications of NDE equipment are presented in Appendix C. The equipment described are used in the following techniques:

- visual inspection;
- methods based on electromagnetism including MPI, Magfoil, magnetography and EMD;
- AC potential drop;
- ultrasonic testing including, thickness measuring devices, flaw detection and sizing devices, Corroscan and Ultrasonic Torch;
- radiographic testing; and
- remotely operated vehicles and atmospheric submersibles.

Selected manufacturers of equipment for the techniques listed above are included in Table 2.2.


DIN62FE
10 ISO 16
IIW/IIS
1.0 Fe 025
DIN I.Q.I.
IIW I.Q.I.

a) DIN and IIW Penetrameters


4T
1T
2T
IDENTIFICATION NUMBERS.
T
4T
1T
2T
T

b) ASME Penetrameter

Figure 2.14 Typical Penetrameters [2.3]

TABLE 2.2
SELECTED LIST OF MANUFACTURERS OF OFFSHORE NDE EQUIPMENT

	NDE Method					
Company	Visual	Electro-magnetism	ACPD	UT	RT	Other
Baugh & Weedon				+		
B.I.X.					+	
Danish Welding Institute				+ (pipelines)		
Henrichs & Walther		+ (Magfoil)				
I.S.E.						+ (ROVs)
Krautkramer-Branson				+		
Magnetische Pruefanlagen		+ (magneto-graphy)				
Nikon	+					
Nortec				+		
Oceaneering						+ (Diving support)
OIS		+ (MPI)		+	+	
OSEL	+	+ (MPI)	+			
Panametrics				+		
RTD				+ (pipelines)		
Sonic Instruments				+		
Thorburn Technics		+ (EMD)				

2.3 Assessment of NDE Methods and Equipment

In this section the NDE methods and equipment already described will be assessed on the basis of information obtained for the study and on the following criteria:

- application; addressing construction type and detail, type of defects anticipated, operation mode;
- accessibility; addressing weather conditions, water depth and currents, visibility, coatings, marine growth, structural geometry and inspection zone;
- reliability; addressing both procedures and equipment;
- cost; addressing cost components and cost reducing measures.

The assessment will also contain recommendations which would improve the performance of the methods.

2.3.1 Visual Inspection

The complexity of work, depth of water, risk and economics must be evaluated on a project specific basis to determine the best method for visual examination. Because of the rapid emergence of underwater technology, it is normally necessary for operators to do their own evaluations in close consultation with diving companies and ROV operators. Demonstrations, testing, and previous performance records are all used to help make choices. Because ROV's, manned submersibles and similar equipment are often purpose designed, comparative evaluations are not meaningful without first knowing the detailed requirements of the job.

To illustrate reliability of visual inspection, the results of a Shell Expro experiment are presented[2.8]. The trials were performed on 6 T-nodes varying in size from 6 in. to 18 in. diameter chord and 3 in. to 18 in. brace. NDE testing was conducted in a steel tank having dimensions 7 m long x 4 m wide x 3 m high. Fatigue cracks of between 5 mm and 610 mm long were introduced in several nodes. It can be inferred from data in Table 2.3 that the average length of surface cracks found in the cleaned nodes was

23% with a standard deviation of 19% compared to 79% in the uncleaned nodes with a standard deviation of 8%. This large difference of detection probability and sizing may have been attributable to the fact that the uncleaned nodes had larger proportion of the large cracks.

Individual diver performances are presented in Table 2.4.

It can be concluded from the data in Tables 2.3 and 2.4 that visual inspection of node welds is unreliable for smaller cracks (up to approx. 200mm), but it can provide reliable results when monitoring critical modes for structural integrity (large, open fatigue cracks).

These is an increasing tendancy to reduce the overall dependency on the diver or underwater examiners' interpretations of the visual data. Rather, it is relayed to the surface support group where it is viewed and evaluated by appropriately trained personnel who are not encumbered with having to cope with the underwater environment. Still photography, and even more important, audio and video transmissions in real time are rapidly improving diver effectiveness. These improvements facilitate the use of simple and effective ways of recording visual and audio information for future detailed and comparative evaluations and documentation. There is also a need for improvements in the following areas to enhance the visual inspection technique:

- stereo photography and stereo video recording;
- fibre optics for close visual examination;
- surface monitoring;
- recording and documentation;
- imaging systems optical or acoustical, for waters with low visibility.

TABLE 2.3

DISTRIBUTION OF CRACK SIZES[2.8]

Size (mm)	0-10	11-20	21-40	41-100	101-200	201+
Cleaned Nodes (Nos. 1,2,3,4)	4	2	4	1	3	0
Uncleaned Nodes (Nos. 5,6)	0	2	4	1	1	5
Total	4	4	8	2	4	5

TABLE 2.4

INDIVIDUAL DIVER PERFORMANCE ON VISUAL INSPECTION[2.8]

	Diver No. 1	2	3	4
Nodes 1,2,3, and 4 (Cleaned)				
Total length of cracks to be detected	666mm	666mm	666mm	666mm
Actually detected	270mm	290mm	41mm	0mm
Percentage Success	41%	44%	6%	0%
Uncorrelated Defects	190mm	269mm	612mm	0mm
Percentage Uncorrelated to Total length to be detected	29%	40%	92%	0%
Nodes 5 and 6 (Uncleaned)				
Total length of cracks to be detected	2551mm	2551mm	2551mm	2551mm
Actually detected	2180mm	2258mm	1816mm	1785mm
Percentage Success	85%	89%	71%	70%
Uncorrelated Defects	150mm	226mm	115mm	238mm
Percentage Uncorrelated to Total length to be detected	6%	9%	5%	9%

In summary, visual inspection regardless of whether it is conducted using divers, personnel in submersibles, controlled atmosphere suits or remotely operated vehicles, should be considered as a primary, general investigation method. It is effective and fundamental for assessing the general condition of underwater structures, locating gross defects and in some cases determining the necessity for more detailed examination. The underwater environment produces a very broad range of psychological and physiological stresses on the human operator. It adversely affects human sensory perceptions, especially visual activity. Hence, the need arises to assist the underwater operator by designing his tasks to be simple and primarily non-interpretive .

2.3.2 Methods and Equipment Based on Electromagnetism

2.3.2.1 MPI

The previously mentioned Shell Expro Experiment[2.8] also evaluated the performances of divers using MPI equipment. Eight divers participated and four different magnetization methods were used. Tables 2.5 and 2.6 summarize collective and individual results. It was discovered that while there was a high and consistent level of crack detection ($\bar{x}$= 90% and σ= 8%), there was also a high incidence of uncorrelated results ($\bar{x}$=40% and σ=44%). It was further reported that no significant differences in equipment types could be found. However, the highest success in locating cracks was achieved using the closed loop conductor and a permanent magnet. The permanent magnet was used in combination with parallel conductors to detect and confirm small cracks. With permanent magnets, only small parts of the weld could be covered because the poles were very close. The advantages in using permanent magnets are that there is no electric supply and both weight and size allows easy handling for the diver, however there are several disadvantages as well:

- as a result of the static magnetic field induced by permanent magnets, the test area must be entirely magnetized to saturation before the leakage field from small defects will be detectable;

TABLE 2.5

SUMMARY OF MAGNETIC PARTICLE INSPECTION RESULTS[2.8]

Node and Crack Identification (Size)	Detection Success	Total Length of Cracks to be Detected	Actually Detected	Uncorrelated Defects Reported
Node Ref. No. 1				
1-0 (185mm)	5 out of 5	925mm (100%)	805mm (87%)	245mm (27%)
Node Ref. No. 2				
1-0 (110mm)	5 out of 5	600mm (100%)	550mm (92%)	752mm (125%)
2-0 (10mm)	3 out of 5			
Node Ref. No. 3				
1-0 (88mm)	19 out of 19	3211mm (100%)	2838mm (88%)	1557mm (48%)
1-1 (5mm)	16 out of 19			
1-2 (10mm)	16 out of 19			
2-1 (20mm)	19 out of 19			
2-2 (23mm)	19 out of 19			
2-3 (15mm)	16 out of 19			
3-0 (8mm)	3 out of 19			
Node Ref. No. 4				
1-0 (110mm)	13 out of 13	2496mm (100%)	2139mm (86%)	132mm (5%)
1-1 (26mm)	10 out of 13			
1-2 (32mm)	11 out of 13			
1-3 (24mm)	11 out of 13			

TABLE 2.6

INDIVIDUAL DIVER PERFORMANCE ON MAGNETIC PARTICLE INSPECTION[2.8]

	Diver No.							
	1	3	4	5	6	7	8	9
Nodes 1,2,3 and 4								
Total length of cracks to be detected (mm)	1332	1183	914	1613	666	666	192	666
Actually detected (mm)	970	1045	802	1471	635	561	189	659
Percentage Success	73%	88%	88%	91%	95%	84%	98%	99%
Uncorrelated Defects (mm)	29	63	1115	341	618	75	1	444
Percentage Uncorrelated to Total length to be detected	2%	5%	122%	21%	93%	11%	0.5%	67%

Note: Diver No. 2 did not undertake MPI.

- few permanent magnets can meet the requirement of a tangential field strength of 2400A/m which is accepted as a minimum magnetization requirement;
- actual magnetization of the test area is difficult to measure;
- it is difficult to ensure good contact between the pole pieces of the magnet and the component being tested.

No correlation was found between using various magnetic particle inks and probability of crack detection[2.8].

There is more operational experience with MPI than with any other NDE method. Magnetic particle inspection using prod magnetization has been applied under DnV's supervision during annual inspection of steel structures in the North Sea since 1975. However the prod magnetization method has been found difficult to use[2.8]; specifically, maintaining good contact causes some problems.

In the 35 jacket structures that were reviewed by DnV[2.9], magnetic particle testing had been performed at least once on 382 joints. This represented a selection of about 5% of the total number of joints in the structures. A total of 25 cracks were found in 18 joints as shown in Table 2.7.

Surprisingly the smallest crack reported was 6mm long and only three joints were repaired. All the cracks reported were confirmed by surface grinding to penetrate at least 1mm into the material.

A disadvantage of magnetic methods is the inadequate definition of detected defects. Only the length of the defect is indicated whereas the depth is usually the most critical dimension. The use of crack-depth indicators would therefore increase the reliability of the method.

TABLE 2.7

CRACKS OBSERVED AND REPAIRED[2.9]

Crack length in mm	Number of Cracks observed	Number repaired
6-25	10	-
26-50	4	-
51-100	1	-
101-200	7	-
200-940	3	3

Cracks detected by MPI in 35 North Sea Structures 1975-79.

The following improvements are suggested for magnetic methods:

- development of methods suitable for ROV operations;
- alternative detection media with the permanent recording of results combined with crack depth measurements.

2.3.2.2 Magnetography

The magnetographic method has been used for over ten years in the steel industry for fillet testing and continuous weld testing on tubes.

The Magneto Marine Method was first used for underwater inspection of four platforms in the Danish sector of the North Sea in 1977. Due to lack of wider experience with the method, the findings obtained by this technique should be confirmed by conventional MPI method. Preliminary results however indicate that the results obtained are objective, reliable and reproducible[2.5].

2.3.2.3 EMD

The reliability of Electro-Magnetic Detection should be evaluated in the light of the following characteristics:

- no detection probabilities are documented;
- depth estimation of shallow cracks is to a certain extent possible;
- material properties (welds) and geometry (including weld surface geometry) will influence the detection and characterization of defects;
- operational difficulties at the present stage of development.

Limited trials with EMD equipment have been reported. The advantages of EMD as claimed by Thorburn Technics International are:

- no need for removal of such coatings as paint, mud, dirt, rust or slime;
- can be used on rough surfaces;
- can be used both above and underwater;
- system is easy to calibrate and operate.

However, underwater inspection trials using TTI's Mk III Deep Sea are still in progress. Therefore, until more experience is gained, the use of EMD equipment should be limited to a pre-testing on undressed surfaces with MPI back-up of any findings.

2.3.3 ACPD Measurement

The ACPD method has been used for crack propagation monitoring and for inservice crack depth measurements on offshore steel structures both above and below water.

The method was first calibrated in the laboratory for tubular joint fatigue testing[2.7], Fig. 2.15, where an accuracy of at least ± 2mm was obtainable for underwater applications.

For the fatigue of welds in heavy plates of thicknesses up to 100 mm, the method resulted in an underestimation of the crack depth of typically 10-20%, Fig. 2.16.

Crack measurements close to crack edges also led to a systematically overestimated measured value. The required correction factor is a function of the crack depth and the distance from the edge. It can be seen from Fig. 2.17 that, within the crack depth range of 1 to 30 mm, the edge effect will be insignificant if the depth measurement is performed more than 40 mm away from the edge.

Tests[2.10] were also done on curved surfaces, Fig. 2.18. Results from measurements on pipes of 161 mm and 212 mm respectively are shown in Fig. 2.19.

ACPD equipment calibrated for measurements on flat plate, requires a correction factor when taking crack measurements in a corner, Fig. 2.20. The deviation between measured and nominal crack depth can be calculated approximately according to:

$$\Delta d = \frac{L}{2}\left(\frac{1}{\sin\alpha/2} - 1\right) \qquad (1)$$

where α = corner angle
L = electrode spacing

The corrected depth of a crack in a corner is thus given by:

$$d = d_{\text{measured}} - \Delta d \qquad (2)$$

Fig. 2.21 shows results of depth measurements in a 120 degree corner when the crack depth indicator has been calibrated for a flat plate. The deviation between nominal and measured value is between 0.7 mm and 1.3 mm. This is in fair agreement with the calculated deviation of +0.8 mm (α= 120 degrees, L = 10 mm).

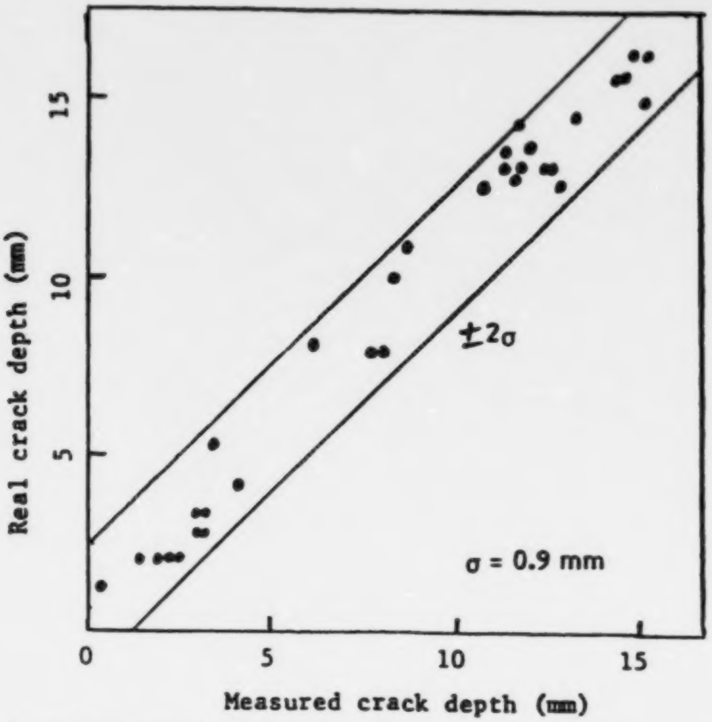


Figure 2.15 Measured Crack Depth Values compared with the results from Destructive Examinations for Fatigue Cracks located at the Weld Toe in a Tubular T-Joint. The Standard Deviation is 0.9 mm and the Mean Deviation is -0.6 mm [2.7]

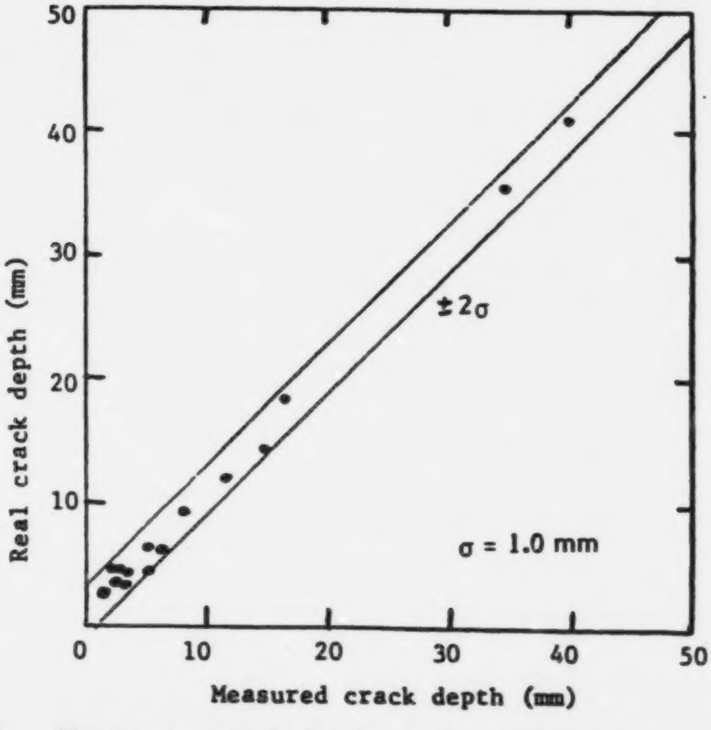


Figure 2.16 Measured Crack Depth Values compared with the Crack Profile Measurements for Fatigue Cracks located at the Weld Toe of the Welds in 100 mm Plates. The Standard Deviation is 1.0 mm and the Mean Deviation is -1.0 mm [2.7]

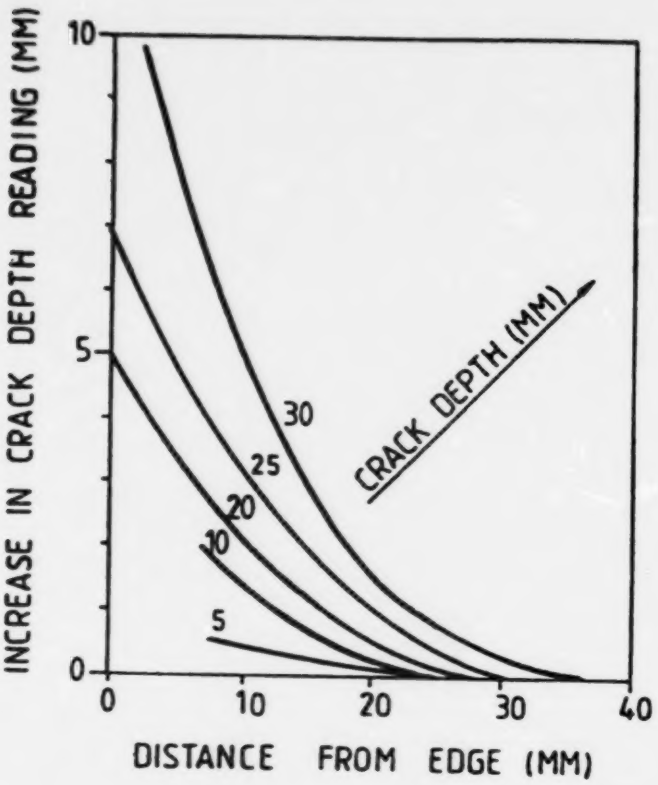


Figure 2.17 Correction Curves for Crack Depth Measurements Close to an Edge 2.10

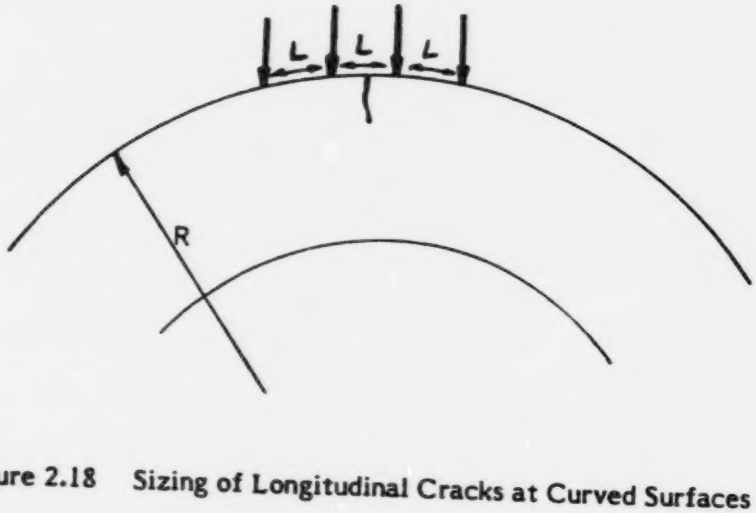


Figure 2.18 Sizing of Longitudinal Cracks at Curved Surfaces 2.10

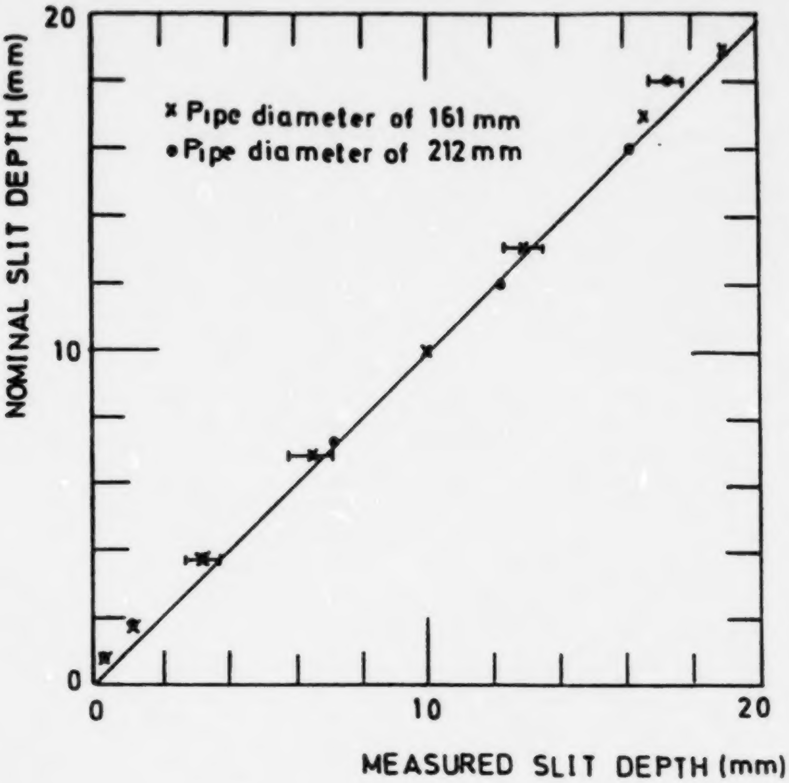


Figure 2.19 Sizing of Slits at Curved Surfaces with the Equipment Calibrated at Plane Surface 2.10

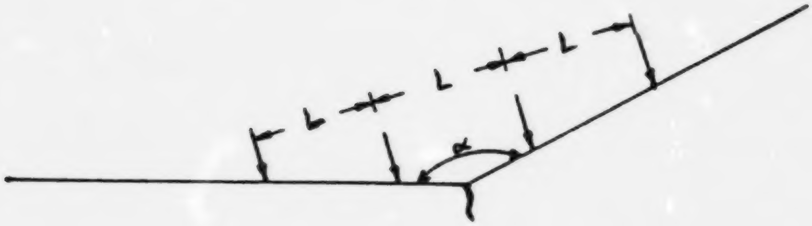


Figure 2.20 Sizing of Cracks in Corners 2.10

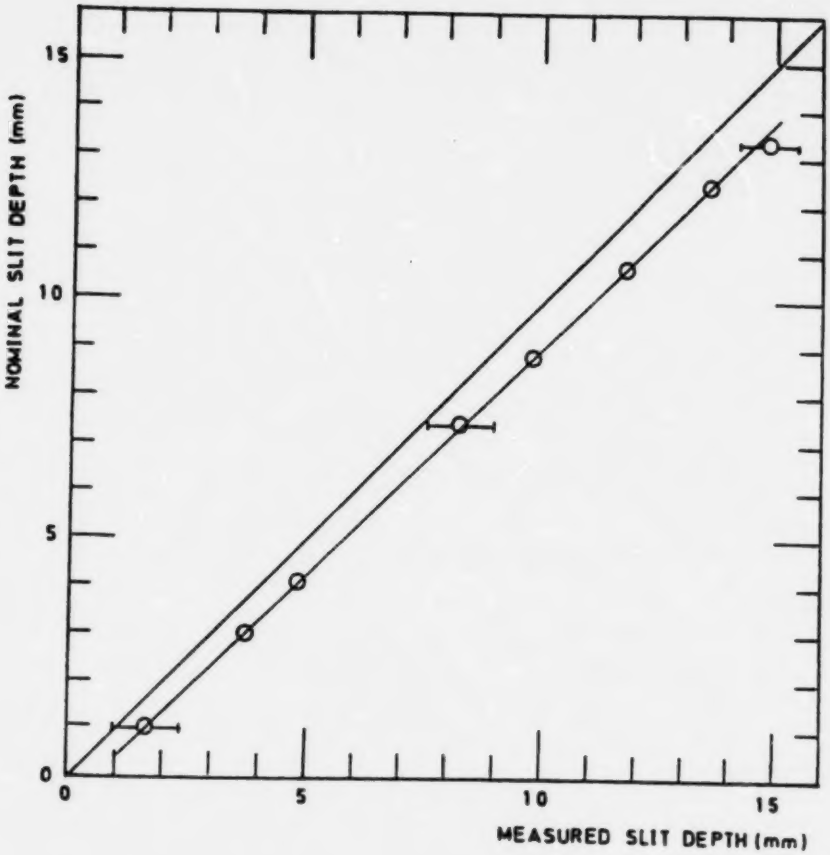


Figure 2.21 Nominal and Measured (not corrected) Slit Depths in a 120° Corner containing a Weld with some Irregular Surface 2.10

Calibration measurements were also done for various length-to-depth ratios (aspect ratios) in order to establish correction curves, Fig. 2.22. These curves shall be used when the crack initially measured depth exceeds 20% of the crack length. If the crack depth exceeds 50% of the crack length, the present crack sizing technique will give no relevant information about the crack depth.

2.3.4 Ultrasonic Testing

The principal application of ultrasonic techniques is flaw detection and sizing, and thickness measurement. Ultrasonic testing has several advantages though its underwater application is still limited. These are:

- high sensitivity, permitting detection of minute defects;
- great penetrating power, allowing examination of extremely thick sections, e.g. up to 10m of steel;
- accuracy in the measurement of flaw position and estimation of flaw size;
- fast response, permitting rapid and automated inspection;
- may be performed with access to only one surface of the object.

The reliability and efficiency of improvement of ultrasonic methods would be enhanced by improvements in respect of the following:

- documentation systems;
- ultrasonic pigs for riser and pipeline inspection;
- automated corrosion- and weld-inspection equipment from diver assisted to use by ROV;
- defect sizing by use of the time-of-flight technique, also for continuous monitoring;
- measurement of material stresses;

and possibly the use of

- acoustic holography or other advanced ultrasonic techiques.

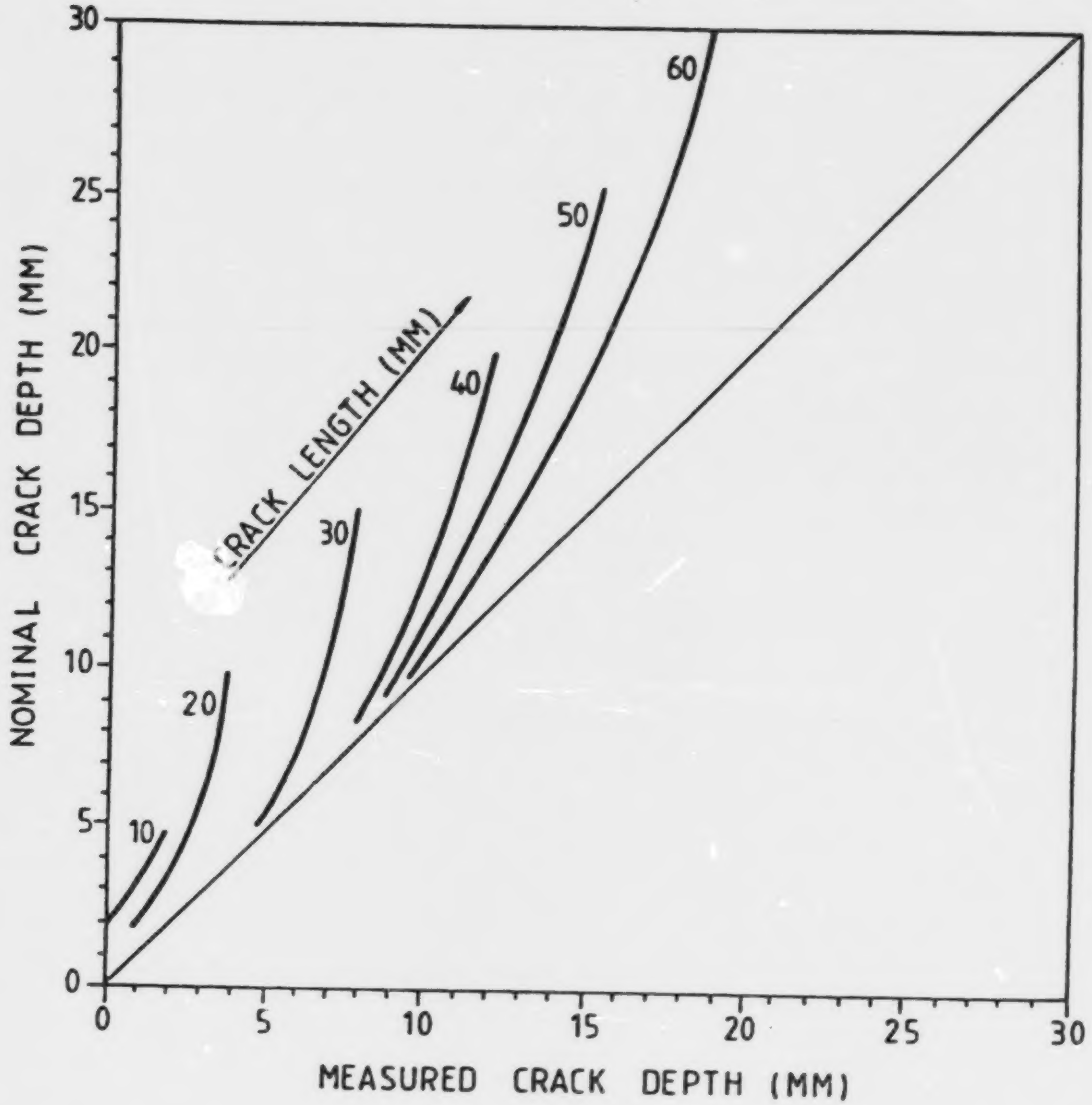


Figure 2.22 Correction Curves for Short and Deep Cracks 2.10

No ultrasonic examination is today performed on concrete structures below water. If needed, it is, however, possible to develop ultrasonic techniques for crack depth and concrete quality measurements.

Test conditions which may limit the application of ultrasonic methods usually relate to one of the following factors:

- unfavourable sample geometry of test object (e.g. complicated tubular joints);
- undesirable internal structure; for example grain size, structure porosity, inclusion content, or fine, dispersed precipitates. Examples of materials difficult to test by ultrasonics are austenitic steel and welds involving nickel base alloys. Penetration of sound into these materials is limited and interpretation of results can be difficult;
- coupling and scanning problems;
- due to high sensitivity, false or irrelevant indications may occur. Type of defect may be difficult to specify;
- operator's qualifications in manually performed UT.

The limitations are also the major source of uncertainties in the UT results.

To illustrate these limitations, the U.K. Welding Institute performed well controlled laboratory tests to compare the performance of variuos UT techniques[2.11]. Some results of this study are presented in Table 2.8. There is a distinct tendency to underestimate the crack depth using UT and also a considerable scatter in the results is noticeable. One would have to add 7-8 mm to the measured flaw size to obtain a 97.5% confidence limit on the maximum size of the actual defect which seems to be too conservative[2.11].

TABLE 2.8

REVISED SIZE MEASUREMENT ACCURACY FOR PLANAR DEFECTS[2.11]

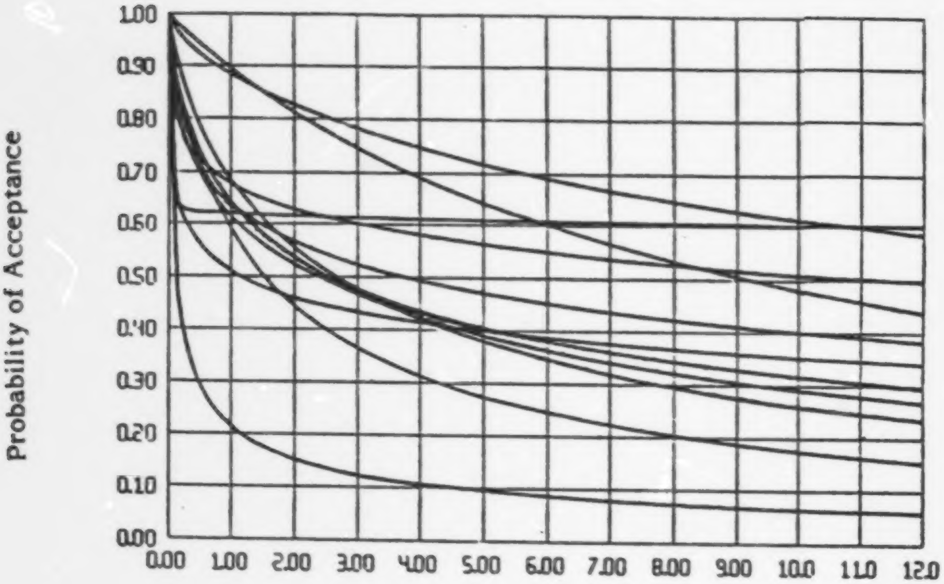
(maximum reported size compared with maximum actual size)

Tests	Mean error $\bar{x}$, mm	Standard deviation Σ, mm	95% confidence limits $(\bar{x} \pm 2\sigma)$, mm	Sizing method
Manual operator 4MHz	-3.1	4.6	+6.1 -12.2	20dB drop, all angles
Laboratory 4MHz*	-3.5	4.1	+4.7 -11.8	20dB drop, 45 degrees
Laboratory 4MHz*	-3.6	5.6	+7.6 -14.8	20dB drop, 60 degrees
Laboratory 4MHz*	-2.3	4.5	+6.7 -11.2	20dB drop, all angles
Laboratory 2MHz*	-3.2	4.0	+4.8 -11.2	Maximum amplitude, 45 degrees
Time-of-flight	-0.5	2.2	+3.8 -5.0	Time measurement

* indicates that these data are not normally distributed

Performance of the operator is decisive for the reliability of manually performed UT. In Fig. 2.23, the acceptance curves for twelve ultrasonic operators were compared[2.12]. It can be seen that for a 12 mm deep crack the probability that this crack remains undetected can be as high as 60% by one operator or as low as 5% by another operator. The scatter around the average echo amplitude shows the following pattern in the uncertainties encountered[2.12]:

- operator/inspection uncertainties: 5dB
- defect/specimen variations: 3dB



Defect Height (mm)

Figure 2.23 Acceptance Curves for 12 Different Ultrasonic Operators 2.12

These values also demonstrate that the main uncertainty stems from the operator.

The underwater use of manually operated UT equipment is prone to even more human error due to harsh environmental conditions. Partial solution to this problem is TV monitoring and surface CRT display so that the diver's interpretation would be limited.

More promising developments are based on automation, and computer control and data logging (Corroscan, P-scan) where the diver's involvement may be limited to the installation of the equipment.

2.3.4.1 Wall Thickness Measurements with UT

Wall thicknesses can be measured using normal, e.g. transmitter/receiver type probes. It is important to be aware of the possibility of erroneous measurements due to a possible water (or paint) layer between probe and object. In general A-scan type equipment gives more reliable readings under all conditions as it allows for better interpretation of the echoes and the echo pattern including the use of multiple echoes for thickness determination. Digital wall thickness meters are, however, usually smaller and easier to handle, but require a smooth, flat surface for reliable use as they usually rely on elapsed time to the first back wall echo for the thickness measurement. This may require grinding of the surface to bare metal even in the case of very modest surface corrosion. It is further recommended that at least 3 individual measurements be taken and reported from each measuring point and that spurious readings also be reported.

For wall thickness measurements the readout or recording equipment may be kept above water, provided there is a satisfactory communication system between diver and surface interpreter and that an adequate system for determination of measurement position has been established.

The accuracy of wall thickness measurements is about 0.5-1.0mm in corroded areas and may improve to 0.1mm on very smooth surfaces.

Automatic recording of internal corrosion has an accuracy of about 0.5mm (standard deviation) in the measured wall thickness and a high degree of reproduceability with a lateral resolution better than 2.5mm.

Manual ultrasonic weld examination is difficult and timeconsuming to perform under water.

2.3.4.2 Corrosion Pit Measurement

Conventional ultrasonics will not function on pit-corroded surfaces because of spurious signals caused by scattering.

The Southwest Research Institute (SWRI) developed a computer-controlled system using a focused transducer concept. The scanning of the transducer over the corroded plate and its alignment over the pit center are performed automatically by the high-speed data acquisition system. Pattern analysis is used to reject wave forms with high probability of having a spurious signal instead of a back-surface reflection. The average error in the thickness measurements was 4%. The system was developed for underwater use and successfully tested on harbor H-pile structures[2.13].

2.3.4.3 Corroscan

The Corroscan system has been operated in the North Sea since June 1981 and a large number of risers and pipelines have been successfully inspected in selected areas[2.14].

The Corroscan system, developed by DnV, has the following applications and benefits:

- complete mapping of selected areas of submerged pipelines and risers, horizontal and vertical sections OD 10-3/4" and larger. Bend sections with radius of curvature greater than 32" (3D bend for a 10-3/4" pipe);
- storage of all data for more comprehensive analysis onshore and comparison with possible re-inspection data;

- on-site calibration, storage of calibration data;
- reproducability adequate for calculation of corrosion rates;
- no special ultrasonic training required for divers;
- high inspection speed compared to manual testing.

2.3.4.4 Ultrasonic Torch

The Ultrasonic Torch is a new system with little operational experience documented[2.15]. Trials have been carried out by divers with and without experience in ultrasonic testing with the result that the torch was easy to use. During the trials, the torch was used at depths of up to 120 m and it appeared that there would be no difficulty in using the torch at its design depth of 200 m.

2.3.5 Radiography

Although radiographic testing is by far the most commonly used method for above water weld examination, underwater applications are not common.

However, radiographic examination has several advantages, provided that a dry underwater habitat can be supplied:

- radiography will detect both surface and internal discontinuities which are volumetric in form;
- planar defects can be detected provided they are oriented parallel to the radiation beam;
- the radiograph provides a permanent record of the test which can easily be reexamined.

Despite the advantages of radiographic examination cited above, several disadvantages are also inherent:

- access to both sides of the test object is necessary to produce a radiograph;
- the shapes of the test object may make it difficult to produce a radiograph with useful information;
- discontinuities such as cracks, laminations, lack of fusion, etc., must be lined up with or parallel to the x-ray beam to be detected clearly;
- choice of radiation energy for a particular thickness of weld is a critical factor;
- personnel must be qualified. Proper interpretation of films requires extensive training and experience.
- x-rays and gamma rays are hazardous. Irradiation of the human body will increase the risk for developing cancer and genetic defects. Such radiation cannot be detected by any of the human senses and proper instruments must be used to check the radiation level. Due to the radiation danger, limitations may be imposed upon time and place of radiography;

A systematic investigation of the reliability of RT findings was performed as a part of the Nordtest Project No. 72-76[2.16].

A number of different types of defects were investigated[2.17]:

Porosity (A):	2
Lack of fusion (C):	10
Lack of fusion combined with lack of root penetration (CD):	12
Lack of root penetration (D):	36
Total number of defects:	60

The distribution of the height and types of the defects are shown in Fig. 2.24. The test plates were radiographed according to IIW Class B and the films interpreted independently by 2 radiographic interpreters according to IIW degree 1-5.

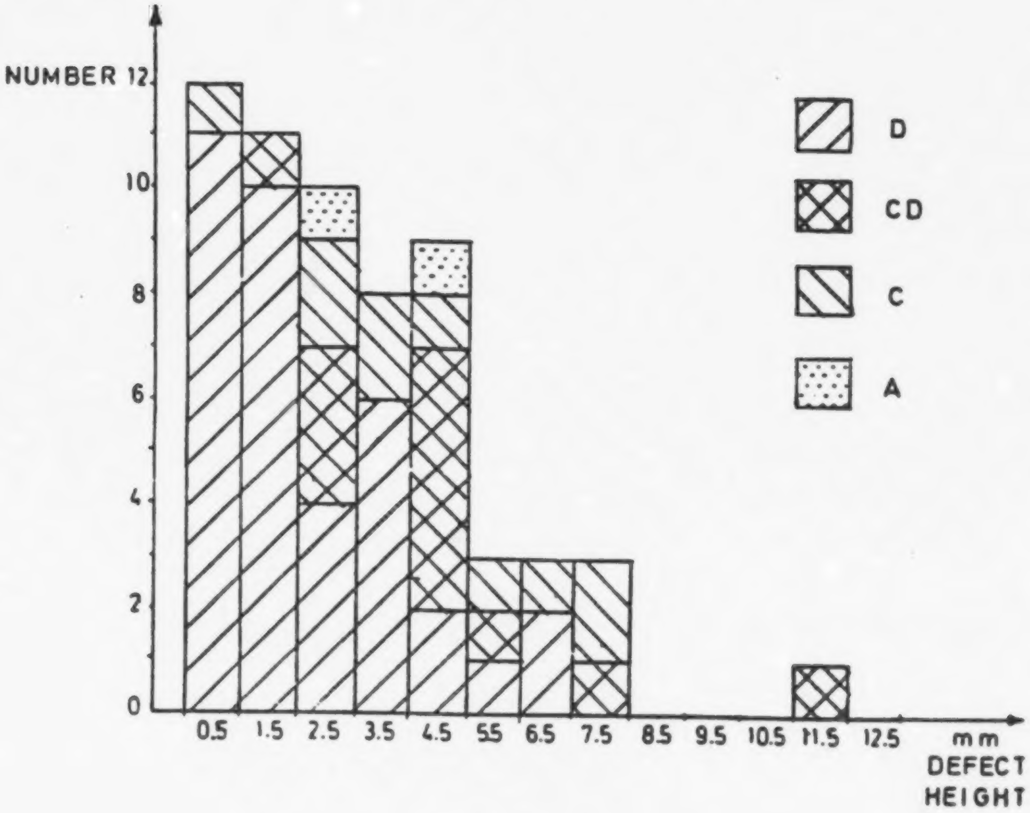


Figure 2.24 Distribution of Defect Height and Type 2.17

There is no obvious parameter to correlate with defect height from a radiograph. However, Fig. 2.25 shows the correlation between IIW degrees and defect height. Table 2.9 gives information on defect type estimated by using RT compared to the real defect type found by destructive testing.

TABLE 2.9

DEFECT TYPE ESTIMATED BY RT[2.17]

		Defect type estimated by RT				
True Defect Type		A	B	C	CD	D
Porosity	(A)	0.5		0.5		
Lack of Fusion	(C)	0.2	0.2	0.4		0.2
Lack of Fusion combined with Lack of Root Penetration	(CD)		0.1	0.3	0.0	0.6
Lack of Root Penetration	(D)	0.0	0.1	0.1		0.8

It can be seen from Table 2.9 that lack of root penetration (D) is estimated quite well by RT, giving correct defect type in 80% of the cases. A correct type estimation of lack of fusion (C) seems difficult (40%), whereas lack of fusion combined with lack of root penetration (CD) is most often estimated as lack of root penetraion (60%).

Finally the distribution of IIW degrees for the two radiographic interpreters is given in Fig. 2.26.

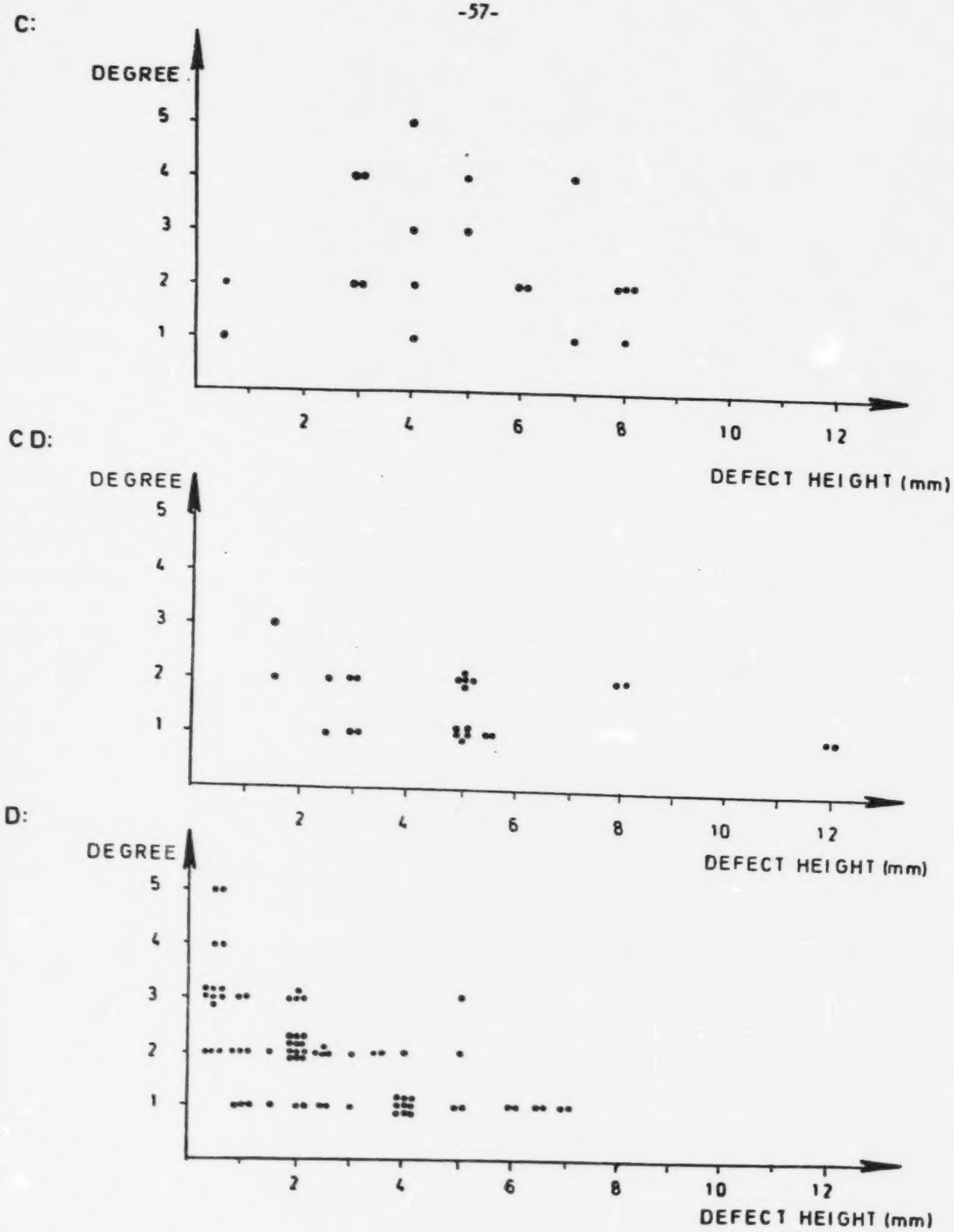


Figure 2.25 Observations of IIW degrees 1-5 versus defect height during radiographic weld examination for defect types lack of fusion (C and CD) and lack of root penetration (D). 2.17

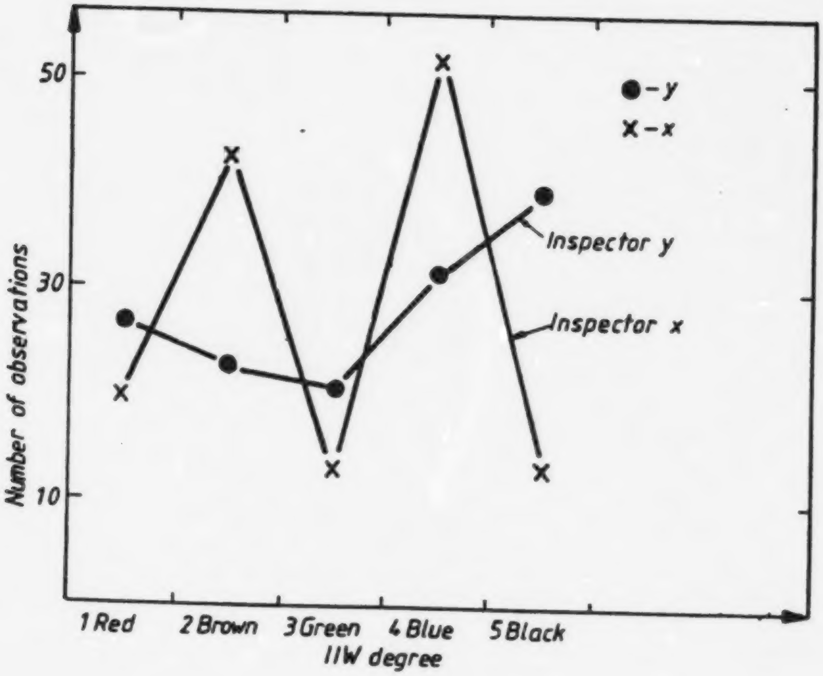


Figure 2.26 Distribution of IIW degrees for two radiographic interpreters 2.17

In most instances, radiographic techniques are employed in dry habitats underwater, however, when RT is performed underwater in wet conditions, it is necessary to account for the sensitivity degradation due to the water layer which must be penetrated. The parameters affecting radiographic sensitivity are listed in Table 2.10.

2.3.6 Remotely Operated Vehicles and Atmospheric Submersibles

2.3.6.1 Manned Submersibles

2.3.6.1.1 Manned Vehicles

One of the main advantages (related to NDE technology) in using manned vehicles is that long umbilicals between measuring device and data-gathering units are eliminated. Hence results are immediate and data interpretation can be performed on-the-spot.

2.3.6.1.2 Atmospheric Diving Suits

The ADS systems are reported to be safe, comfortable, and cost-efficient option to saturation diving and remotely operated vehicles.

2.3.6.2 Remotely Operated Vehicles (ROVs)

There are over 100 different makes of tethered free swimming ROVs on the market, however the reliability of many of these ROVs offshore is questionable. In a recent study[2.18] of the many ROV's available, the following list was prepared indicating ROV components in decreasing failure frequency:

- underwater lights;
- subsea electrical connectors, cables and cable terminations;
- submerged electrical motors;
- vehicle electronics;
- vehicle hydraulics;

TABLE 2.10

RADIOGRAPHIC SENSITIVITY[2.3]

DEFINITION			CONTRAST	
GEOMETRY AFFECTED BY	FILM GRAININESS AFFECTED BY	SCATTERING AFFECTED BY	SUBJECT CONTRAST AFFECTED BY	FILM CONTRAST AFFECTED BY
Source size (small source preferred)	Type of film (some films are more grainy than others)	Energy (KEV) of radiation	Thickness differences in specimen (the greater the change in thickness the greater the contrast	Type of film (some films give better contrast than others at a given exposure)
Source-to-film distance (longer distance preferred)	Type of screen (Flourescent screens decrease definition)	Scatter control techniques a) Screens b) Masks c) Collimation d) Plugs e) Filters f) Shot	Density differences in specimen (the greater the change in density the greater the contrast)	Density of film image (the darker the film the greater the contrast)
Specimen-to-film distance (shorter distance preferred)	Radiation energy (KV) used (higher voltages produce more graininess)		Radiation energy (KEV) used (higher energy, less contrast, lower energy, more contrast	
Source offset (source must be on line perpendicular to plane of interest)				
Screen-to-film distance (contact preferred)				
Abruptness of thickness changes in specimen (uncontrollable)				

Moreover, many ROV systems suffer from the following disadvantages in moderate sea states during the launch and retrieval phases:

- pendulum motions of ROV/launcher during hoisting is not sufficiently prevented;
- connecting of launcherless ROVs to the handling gear must normally take place in the surface and hazardously close to the support station;
- strong jerks in the hoisting line often occur when lifting launcherless ROVs out of the waves;
- the umbilical is very vulnerable to entanglement and destruction when separate hoisting line for the ROV/launcher is used;
- lacking heave compensation of the launcher makes ROV homing and clamping to the launcher difficult and hazardous;
- ROV/launcher is insufficiently protected by fenders. Firm mounting of sub systems to the ROV-structure often make them vulnerable to impacts.

In general it has been found that the best results are obtained by using a heavy heave compensated launcher which is handled by a reinforced umbilical and transports the ROV to its operating depth (like the RCV-225).

3. PROSPECTIVE NDE TECHNIQUES FOR OFFSHORE STRUCTURE INSPECTION

There is ongoing research and development in underwater NDE techniques. These developments mainly address the following considerations:

- cost-effectiveness of inspection and maintenance;
- quality of inspection;
- installations in deeper waters.

As an example, summaries of the main NDE research projects currently underway in the UK are given in Appendix D.

The new systems being developed are characterized most of all by the trends towards automation and remote control of equipment, real time signal processing and optimization of NDE efforts. In particular, processing of signals using powerful microprocessors and computers brings new dimensions to both traditional NDE techniques (ultrasonics, radiography, electromagnetic methods, visual methods) and to techniques still under intensive laboratory development (tomography, acoustical holography). Hardware and software are equally important in the computerization of NDE techniques.

Some of these new developments will be discussed in this chapter. It must be pointed out, however, that even though the present state-of-the-art in these techniques may not allow their immediate application to underwater NDE, some of them can come into use in the foreseeable future or their application to fabrication inspection can have a great impact on the quality of the offshore structures and subsequently on the need and frequency of underwater inspection and/or monitoring.

3.1 Inspection Methods

3.1.1 Advanced Ultrasonic Testing

The first ultrasonic testing system was built in 1930. The breakthrough in UT method was the introduction of the pulse-echo technique in 1942. Since then UT instrumentation underwent considerable developments. The most commendable achievement is the ultrasonic diffraction technique measuring the time-of-flight in addition to amplitude recently developed at Harwell. Other developments to be mentioned are defect reconstruction by phased arrays and ultrasonic holography with focussing. Of course automation and computerization play a major role.

3.1.1.1 P-Scan

P-Scan (Projection image Scanning) was developed by the Danish Welding Institute. This technique has been developed for automated ultrasonic weld inspection. Using one or more ultrasonic probes attached to a scanner, all echoes from defects (without a preset detecting level) are permanently recorded and later processing the logged data, a complete, three dimensional location of weld defects is reconstructed.

3.1.1.2 Rotoscan

Rotoscan is a multichannel automated ultrasonic system developed by RTD (Roentgen Technishe Dienst) for inspection of pipeline welds.

3.1.1.3 SUTARS

SUTARS (Search Unit Tracking And Recording System) is a system developed at the Southwest Research Institute, Texas (SWRI).

Scanning with the ultrasonic search unit is done manually. A transducer array is used to locate and automatically record the position of the search unit (including skew). A pulse-echo ultrasonic technique is used to detect, locate and characterize the defects. All indications are also automatically recorded and the operator obtains information in real-time on the coverage of the volume to be inspected. The logged data is then processed and a B- and C-scan of the inspected volume reconstructed.

3.1.1.4 Time-of-Flight Method

The ultrasonic time-of-flight diffraction for detection and sizing of defects in steel sections has been developed at AERE (Atomic Energy Research Establishment), and was developed as an automated inspection procedure[3.1].

This method interprets time delays of the crack edge diffracted signals using the lateral wave (corresponding to the fastest route between the transmitter and the receiver) for timing reference.

After proving capabilities of the method (best sizing accuracy among ultrasonic techniques, Harwell is launching a development program to expand application of the time-of-flight method to complex geometries and should be completed in 1985/86[2.11].

Another sophisticated system using the time-of-flight analysis for NDE of turbine disk rims of a very complex geometry has been developed at the Southwest Research Institute (Texas)[3.2]. The system allows rapid scanning and crack-sizing.

3.1.1.5 TREES

Turbine Rotor Examination/Evaluation System (TREES), developed at the Southwest Research Institute (Texas), is described here to demonstrate NDE technology available in other industries. It uses a focused search unit and high-speed automated data acquisition and processing system. The processed data is then used as input to a program for fracture mechanics failure analysis which predicts the residual lifetime for the rotor in question.

3.1.1.6 Phased Arrays

At Fraunhofer Institute, Saarbruecken, West Germany a phased array system was developed for defect reconstruction and classification[3.3, 3.4]. The principle of the system incorporates a sound beam which is electronically steered over a specimen sector in a fan-like fashion. Using different probe positions in the array, a defect can be reconstructed and positioned through individual image points.

3.1.1.7 Ultrasonic Holography

Ultrasonic holography is analogous to optical holography with the exception that the object is on focus in a plane. The system uses a matrix of focussed ultrasonic transducers which act both as transmitters and receivers. The signal amplitude, time and phase are monitored using an electronic gate. The phased signals are then electronically processed to reconstruct a focused acoustic hologram[3.5].

3.1.2 Enhancement of Electromagnetic Methods

It has been demonstrated that MPI is the most widely used technique for detection of surface breaking cracks in offshore structures. It is felt though that this method can, if further developed, yield much more quantified information about the defect size, character and location. The UK Welding Institute, responding to the needs of various sectors of industry, is launching a project entitled "Optimized Magnetic Particle Inspection Technique for Welded Joints".

Within this project, finite elements will be used to model the magnetic leakage field caused by both geometry and defects of the welded joint. Also, reliability of MPI shall be systematically investigated to account for spurious indications.

At Harwell, a pulsed eddy current method is being developed to give multiple frequency data so that greater accuracy and discrimination can be achieved on crack depths as compared to single frequency systems. Special analogue circuitry shall provide signal processing of digitized eddy current signals.

3.1.3 Computerized Tomography

Computerized tomography, reconstructing cross-sectional images of inspected specimen, was developed and still is mainly used in medicine. Tomography evolved from radiography when exposures of the object were taken from different angular positions. After the reconstruction algorithms were developed[3.6, 3.7], radiographic images were digitized and powerful computers used (e.g. CDC 7600[3.8]) to reconstruct the sectional views (tomograms). Depending on the size and mass of the inspected object, gamma rays from Iridium-192, Cesium-137 or Cobalt-60 isotopes as well as lower energy x-rays or even neutron beams have been used to generate tomographic images.

3.1.4 Enhanced Visual Inspection

3.1.4.1 CARTIS

Computer Aided Real Time Inspection System (CARTIS) has been developed by BIX International Services (UK). The system uses a computer and special software to perform the desired functions such as image enhancement, co-ordinate measurements or automatic component inspections.

To demonstrate the degree of enhancement available, the human eye can define a maximum of 64 shades of gray whereas for a TV camera, each frame of information will consist of a matrix of 512 x 512 pixels and each can have one of 256 gray scales.

3.1.4.2 Optical Holography

A feasibility study on the use of optical holography underwater for inspection and recording has been undertaken at the Gordon's Institute of Technology, Aberdeen (UK)[3.9]. It has been concluded that optical holography would be successful underwater under the same visibility conditions as would be necessary to produce good photographs. A holographic image can contain 10^{15} bits of information per square meter compared to 10^{10} bits/m^2 possible by high quality photography. A single hologram could, therefore, provide the same amount of information as several thousand photographs.

The best dynamic stability is achieved by the use of a pulsed laser. The attenuation in light intensity with distance from the source would be greater in the water than on the surface and the maximum scene depths of 1-2 m are feasible with laser energies of 1-10 J.

3.2 Prospective Inspection Equipment

Descriptions of prospective NDE equipment are presented in Appendix C. The equipment described are used in the following techniques:

- advanced ultrasonic testing;
- enhanced electromagnetic methods;
- computerized tomography; and
- enhanced visual inspection.

3.3 Assessment of Prospective NDE Methods

3.3.1 Advanced Ultrasonic Testing

3.3.1.1 P-Scan

P-Scan has been used successfully in VERITAS' Corroscan equipment described in Appendix C.

3.3.1.2 Rotoscan

At present a sub-sea version of Rotoscan is built for a 50m depth. Further development for depths up to 250m is considered. As a part of the work, the problem of long cables using glassfiber optics was dealt with.

To inspect complicated welds in tubular joints, RTD is developing a microprocessor-controlled scanner with up to 6-axes controlled movement.

3.3.1.3 SUTARS

SUTARS was developed to eliminate the main disadvantage with manual ultrasonic testing, i.e. the lack of a permanent record whether the CRT is underwater or the inspector has it available also on the supporting boat. The problem is with ensuring that the whole inspected area is covered, with positioning of the probe and recording manually any above threshold indications of the A-scan.

3.3.1.4 Time-of-Flight Method

For the system developed at the Southwest Research Institute, the time-of-flight method allows extensive cost and time savings over the currently used MPI method because it does not require the costly and time consuming removal of the turbine blades[3.2]. (Refer also to section 3.1.1.4).

3.3.1.5 TREES

Since TREES is still being developed, an assessment is not possible at this time.

3.3.1.6 Phased Arrays

The phased array systems are still in the development and laboratory trial stage.

3.3.1.7 Ultrasonic Holography

Holosonics Inc. (USA) spent several years on development of acoustic holography to meet the objectives of underwater inspection[3.10]. This system can be applied by submersible manipulation systems or manually by divers from a lockout vehicle. The flaws can be viewed in real time by an inspector and permanent records kept on videotape, magnetic tape or hard copy prints. Flaws can be located, magnified for close examination and then reconstructed in three-dimensions by utilizing logged data. However, the present state of development of acoustic holography does not yet allow for its commercial use as an underwater inspection tool.

3.3.2 Enhancement of Electromagnetic Methods

Since new methods and systems being investigated at the UK Welding Institute and at Harwell are still in the development stage, an assessment is not possible at this time.

3.3.3 Computerized Tomography

Despite some encouraging results, tomography is still in the development stage and its present use as an NDE technique is limited to very special cases.

3.3.4 Enhanced Visual Inspection

3.3.4.1 CARTIS

Enhanced systems such as CARTIS have a good potential to be used for inspection of offshore structures either operated mannually be a diver or installed on ROVs.

3.3.4.2 Optical Holography

Optical holography has the potential of being used as a part of future inspection equipment installed on ROVs or being used by a diver from a lock-out vehicle.

4. INSTRUMENTED MONITORING OF OFFSHORE STRUCTURES (IMOS)

4.1 General

Present methods of underwater inspection are both risky and expensive in addition to being highly dependent on weather conditions. These methods are applied locally and there is no guarantee that a significant defect will be found. It is not envisaged at present that monitoring systems would substitute NDE, rather complement it. One great advantage of continuous monitoring, as compared to traditional periodic inspection, is that monitoring would not interfere to any significant degree with normal operations on the platform. Recently conducted research and development in instrumented monitoring techniques shows that major contribution to the safety and economy of offshore structures can be made by implementation of such a system. For structures in water depth range of 70-150 m the instrumentation will be used together with diver inspection. For structures in deeper waters, ROVs would provide the complementary inspection.

In view of its significant potential impact on offshore inspection, a discussion on IMOS is presented in this chapter.

4.2 Objectives of IMOS

Monitoring systems can be divided in two basic categories:

1. Monitoring systems which would give warning of catastrophic failures. The objective of these systems would be to prevent loss of life by providing advanced warning for evacuation of the platform
2. Monitoring systems which would give early warning of local failure taking place before the structural integrity of the whole structure is threatened. This would allow repairs to be undertaken.

The latter systems, which can significantly contribute to the prevention of major structural failure will prove most valuable, particularly when deployed in conjunction with NDE.

Such IMOS systems must meet the following objectives:

- detect significant changes in structural response and environment;
- collect, store and evaluate data from the observations of response and environment;
- interface with relevant structural consequence analysis;
- assess the damage in terms of: need for repair, time limit for the repair, need for further inspection, possible limitations in the operations of the structure before, during and maybe also after the repair.

4.3 Description of IMOS

A typical IMOS system (Fig. 4.1) comprises the following subsystems:

- detection and data acquisition subsystem;
- analysis subsystem;
- communication subsystem;
- reporting subsystem.

IMOS further interacts with other subsystems such as DFI, structural reanalysis, inspection, maintenance, etc. In other words, the system must be compatible with an overall design, inservice inspection and maintenance strategy suitable both for the operators and the authorities.

The detection subsystem monitors both the structure and its environment and transmits the data to the data acquisition unit for checking and formatting. The formatted data is then transmitted to the analysis subsystem which performs the relevant analysis (structural reanalysis). The reporting subsystem then provides the competent personnel with the results of the analysis as the basis for decision making. A schematic flow chart presenting various aspects to be considered when designing an IMOS system is shown in Fig. 4.2.

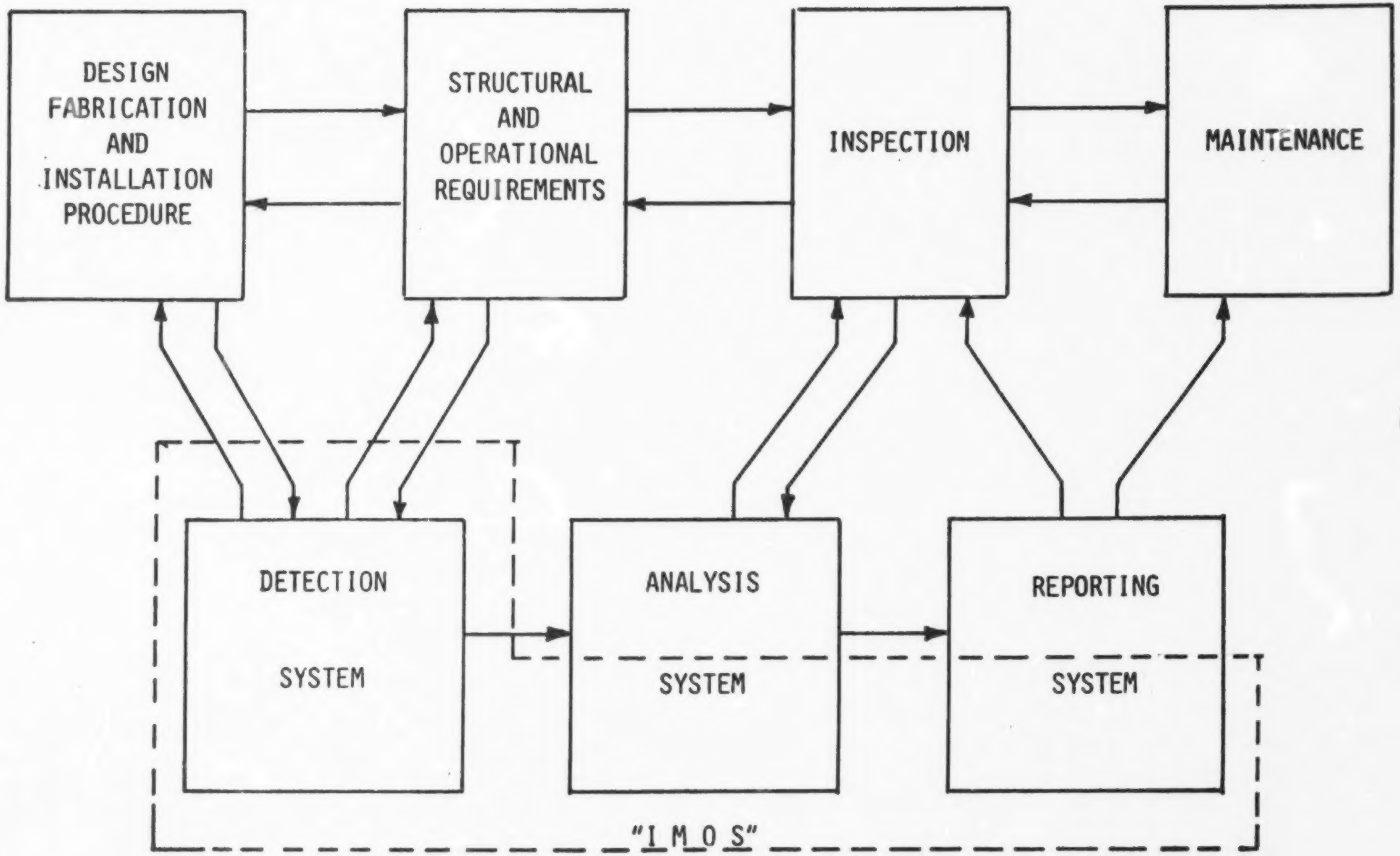
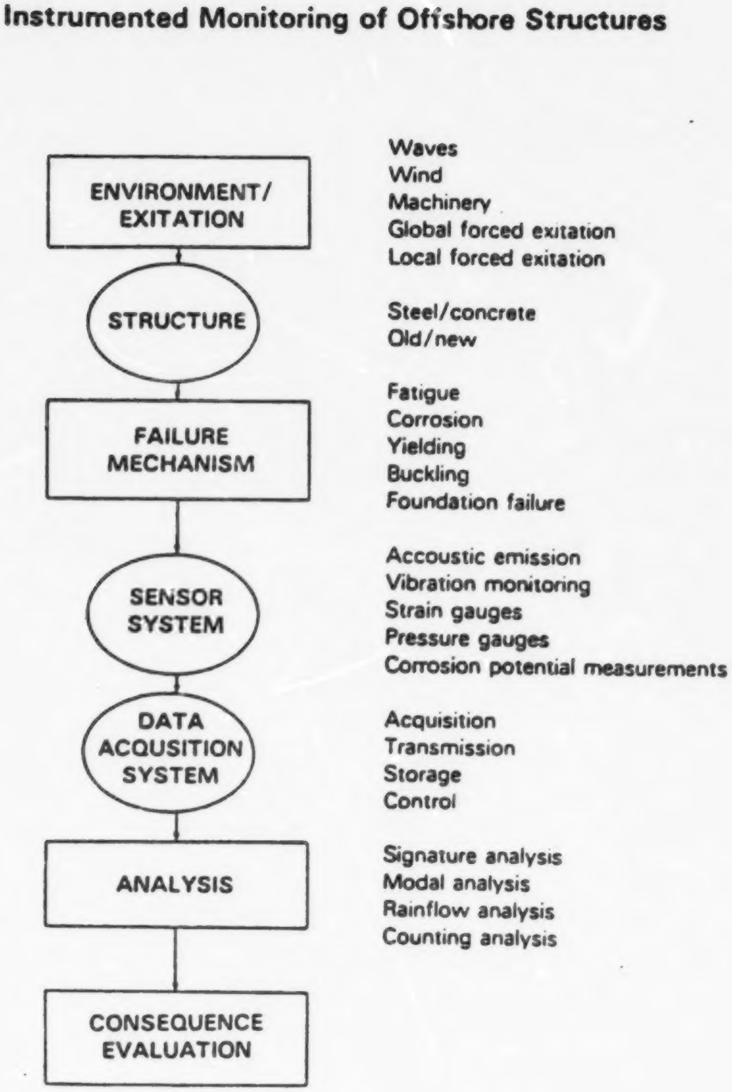

DESIGN
FABRICATION
AND
INSTALLATION
PROCEDURE
STRUCTURAL
AND
OPERATIONAL
REQUIREMENTS
INSPECTION
MAINTENANCE
DETECTION
SYSTEM
ANALYSIS
SYSTEM
REPORTING
SYSTEM
"I M O S"

Figure 4.1 Relation of IMOS to Offshore Surveillance System [4.8]



Instrumented Monitoring of Offshore Structures

ENVIRONMENT/ EXITATION
Waves
Wind
Machinery
Global forced exitation
Local forced exitation
STRUCTURE
Steel/concrete
Old/new
FAILURE MECHANISM
Fatigue
Corrosion
Yielding
Buckling
Foundation failure
SENSOR SYSTEM
Accoustic emission
Vibration monitoring
Strain gauges
Pressure gauges
Corrosion potential measurements
DATA ACQUSITION SYSTEM
Acquisition
Transmission
Storage
Control
ANALYSIS
Signature analysis
Modal analysis
Rainflow analysis
Counting analysis
CONSEQUENCE EVALUATION

Figure 4.2 Items to Consider when Designing a System for Instrumented Monitoring [4.8]

In the following, only the first part of IMOS, the detection subsystem will be discussed. Only those detection techniques will be described which are considered as potentially attractive to be used with IMOS systems.

4.4 Detection Methods

There are a large number of methods available which are suitable for detection of structural damage[4.1]. These methods can be divided into two groups:

- methods for local monitoring;
- methods for global monitoring.

Some local monitoring methods can be used to cover the whole structure.

In selecting a detection method, both detection capability and cost of implementation and operation have to be considered. Also reliability of the system in long term operation is an important factor. The system has to be rugged to continue operating under storm conditions when structural failure would be most likely to occur. A different approach has to be taken in designing an IMOS system for a new structure at the fabrication and installation stage from implementing a monitoring system on offshore structures already in operation. The detection techniques shall be reviewed with preference to monitoring steel structures.

The monitoring approach assumes a fail-safe design of the structure with such degree of redundancy that adequate warning of structural response changes can be given before the loss of structural integrity of the whole structure is imminent. Such early warning would allow repairs without large economic losses.

4.4.1 Vibration Methods

The techniques can be divided into two major groups:

- Passive. This method utilizes vibrations present in the structure from natural sources such as waves, machinery, equipment, etc.
- Active. This method needs an excitation source such as constant amplitude sine sweep (rotating weight or electromagnetic excitation), impulse source using mechanical hammer or small explosions, or random electromechanical excitation with a defined band width.

The active vibration method has the disadvantage of the nuisance and disturbance to the platform personnel caused by the vibrations introduced in the structure.

The principle of vibration methods lies in monitoring and evaluating dynamic response of the structure to external excitation. A regular pattern of response is processed by dedicated computer and changes, in natural frequencies are indicative of structural changes. The change in natural frequencies can be caused by such events as missing member, flooded member, change in foundation, marine fouling or redistribution of live loads on the platform. Usually spectrum analysis of acceleration records is used to determine two flexual frequencies, in two vertical perpendicular planes, and a torsional mode. For example, after a vessel collision with the Buzzards Bay Entrance Tower, the damage underwater was evaluated using vibration technique[4.2]. The tower was analysed using MITs ICES-STRUDL II finite-element program. Table 4.1 shows the change in fundamental flexural natural frequencies caused by damage in various parts of the tower, Fig. 4.3.

Analysis of the Buzzards Bay Tower led to the conclusion that structural damage causing change in natural frequencies of 2% or greater can be detected[4.2]. The most important sources of uncertainty are the long-term changes in mass (marine fouling, flooded members), changes in supporting bottom conditions, and particularly changes in the deck live loads (sloshing liquids in tanks, etc.).

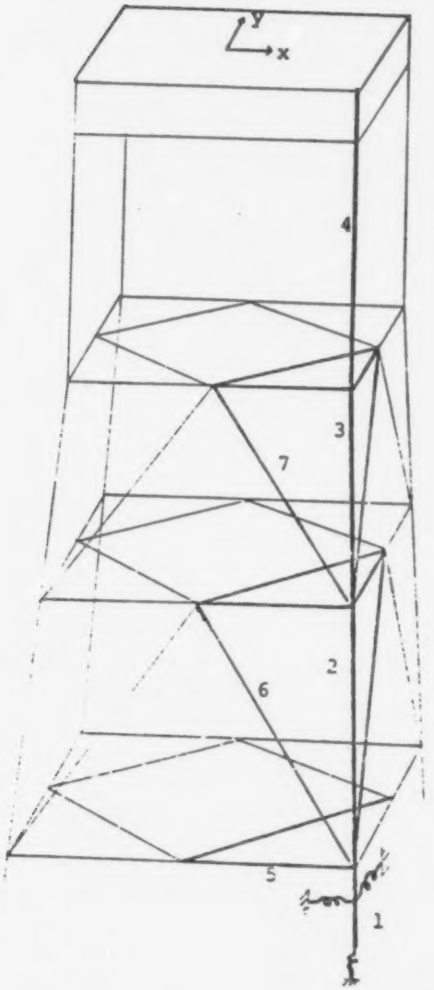


Figure 4.3 Schematic of the Buzzards Bay Tower [4.2]

TABLE 4.1
FUNDAMENTAL FREQUENCY REDUCTION DUE TO DAMAGE[4.2]

Damaged Member		Percent Reduction in Frequency	
		Δf_x	Δf_y
1.	Piling	17.14	17.14
2.	Lower Leg	11.15	11.15
3.	Middle Leg	5.92	5.92
4.	Upper Leg	8.80	8.80
5.	Minor Horizontal	0.12	0.0
6.	Lower K Brace	6.10	0.17
7.	Upper K Brace	7.18	0.0

It depends very much on the computer model and possibly on the capability to monitor and analyse higher freqencies to separate structural damage from these other causes of change in natural frequencies. Even the type of failure may be deduced from relative shifts in frequency.

4.4.2 Acoustic Emission (AE)

When stressed, many solid materials (metals, wood, fiberglass, etc.) generate transient elastic waves as a result of rapidly released energy. Such (acoustic) emissions can be generated by several phenomena, such as local plastic deformation in the vicinity of stress risers, crack initiation, and crack growth or phase transformations.

Piezoelectric transducers can be used to monitor these acoustic emissions and using computerized signal processing with necessary amplification and noise filtering, typical defect signatures can be obtained[4.3]. The frequency range of these acoustic emissions lies generally between 100 kHz and 1 MHz.

Thus by measuring acoustic emissions, it is possible to monitor crack propagation and give warning well in advance of failure and loss of structural integrity. On large structures, a triangulation technique can be used to locate the source of the monitored emissions.

The acoustic emission technique has been used very sucessfully as an NDE tool for inspection of pressure vessels, particularly nuclear[4.4].

AE has potential to be used as a monitoring technique for offshore structures[4.1, 4.5]. It would be best used locally to monitor selected "hot spots" with limited number of transducers.

AE is attractive as a passive system with a limited number of transducers to cover a large area (50 m between transducers seems to be realistic). The method is limited to steels having high signal to noise ratio. Some steel types used offshore (with high fracture toughness) are claimed to have low levels of emissions during fatigue. The signal processing is an important part of the system and must be capable of eliminating extraneous noises.

A significant disadvantage of this technique is its inability to provide reproducible results because after the defect gets "accustomed" to the current stress level, it becomes dormant until reactivated by an increased stress level. The defects would be especially active when high environmental loads (high strain energy) would be acting on the structure during storms when also structural failure would be most probable.

It is generally believed that AE technique has the potential to identify and size the defects, as well as locating them.

4.4.3 Acoustic Pulsing

The U.K. Welding Institute recently patented a novel technique (acoustic pulsing) which can be used for monitoring structural integrity. It is claimed that this technique would overcome some difficulties of both vibration and acoustic emission techniques[4.6].

The principle of acoustic pulsing is to inject a constant acoustic pulse, preferably of ultrasonic frequency, into the structure from one of a network of widely spaced (tens of meters) transducers fixed to the structure. The signal is modified when passing structural members between the input transducer and receiving transducer. A signature of any structural change can be evaluated by comparison with previous records. The technique should be capable of:

- detection of the extension of the flaw;
- location of the region of flaw growth;
- estimating the amount of flaw growth.

This method can be used for overall scanning of the structure.

With only 0.1 W of electrical drive, transmission over 9m has been achieved with a 400 kHz signal. A particular advantage of the method is that pulsing can be repeated during a given monitoring cycle to check the validity of the recorded signal. Inter-transducer distances can be up to an order of magnitude greater for acoustic pulsing than for AE.

The potential of acoustic pulsing has yet to be proven through offshore trials.

4.4.4 Ultrasonic Technique

Principle of ultrasonic technique was described in previous sections. As far as structural monitoring is concerned, ultrasonic scanning may be limited to a selection of critical welds. If three transducers would be used to monitor one circumferential weld, any crack so found could extend around some 30% before being discovered. One ultrasonic probe operating at 1 MHz frequency can scan only a limited area of no more than 4 cm^2. A complete monitoring of a relatively small tubular member may need 100 ultrasonic probes for full monitoring which would be uneconomical.

It seems that ultrasonics would be limited to characterization and sizing of defects located by other methods or to monitoring of a small number of highly stressed "hot spots" in the structure.

4.4.5 Flooded Member Detection

The majority of offshore structures are built by welding together hollow tubular members. Integrity of the members can be monitored by checking on their lead tightness. Various witness techniques can be used to detect flooded members[4.1]. Also ultrasonics can be adapted easily to monitor flooded members taking advantage of different acoustic properties of water and air[4.7]. Pressured air would provide other means for checking the water tightness.

4.4.6 Strain Gauges

Strain gauges are widely used mainly for experimental confirmation of design loads measured on structures during operation. Strain gauge data has been obtained from several offshore structures to check strains calculated from finite element analysis under assumed loading conditions. The data collected and recorded from strain gauge measurement reflects the loading history and provides a valuable input for fatigue life calculations.

A promising development in strain gauge instrumentation is the AILTECH weldable strain gauge. Rugged construction and positive attachment together with waterproof and pre-tested cables makes these gauges suitable for strain monitoring of offshore structures. The AILTECH strain gauges can be used for a wide range of static and dynamic measurements.

A great disadvantage is the poor strain gauge reliability particularly underwater. A failure rate up to 40% in a 4-year period indicates a limited application of this technique for long-term (more than 20 years) monitoring of offshore structures[4.1].

4.4.7 Attitude Measurement

A measurement of deviation of offshore structure attitude from its initial value can be monitored. Also the rate of change in attitude of the structure can be measured. It seems that this technique, due to lack of sensitivity, could be used for global monitoring of the overall structural integrity giving a warning of pending catastrophic failure to prevent the loss of the platform crew.

4.4.8 Other Techniques

Some other techniques such as magnetic methods, electric current testing, microwave testing, thermal and infrared technique, radiographic technique are believed to have little potential as a part of IMOS[4.1]. Underwater enhanced TV viewing (including colour and stereo technique) and sonar technique (Sound Navigation and Ranging) have potential to be developed in connection with inspection done by ROV's and manned or unmanned submersibles.

4.5 Example of IMOS

Figure 4.4 shows an example of IMOS based on three monitoring techniques[4.8]:

- strain gauge measurement at selected locations for fatigue monitoring;
- integrity monitoring (global) using vibration technique;
- local monitoring of "hot spots" using acoustic emission.

The instrumentation will be based on special data acquisition modules, placed on the structure near the sensors, using cableless transfer of data to the surface logging and preprocessing units. From here, the data will be transferred to an onshore data analysis centre for further processing and analysis. This system would avoid the use of underwater signal and power cables as these are very vulnerable to damage in the harsh marine environment. The modules will be placed in watertight cabinets of glassfibre reinforced polyurethane with power supply from lithium batteries with an expected life of 5 to 10 years. The hydroacoustic transmission system is capable of transferring data at a rate up to 2 kilobaud within a distance of 2-3 km. This IMOS system has been developed by DnV for Norsk Agip A/S.

4.6 Equipment for IMOS

4.6.1 Vibration Detection Equipment

Equipment using an "active" approach to vibration detection is produced by Syminex located in France. The Syminex Vibrodetector gives a shock to bracings in the steel jacket via a pneumatic impactor and measures the resulting vibrations. The signals (excitation and response/force and acceleration) are then transmitted by a waterproof armoured cable to the data acquisition equipment located on the platform deck where they are filtered, digitized and recorded on magnetic tape. During measurements, the recorded signals can be treated on site by the data acquisition mini-computer. Readings from subsequent inspections are then compared to readings obtained from the previous inspection(s) which have been stored in the memory of the Fourier analyzer, thereby indicating the existance of cracks. This allows the results of each inspection to be known immediately on site.

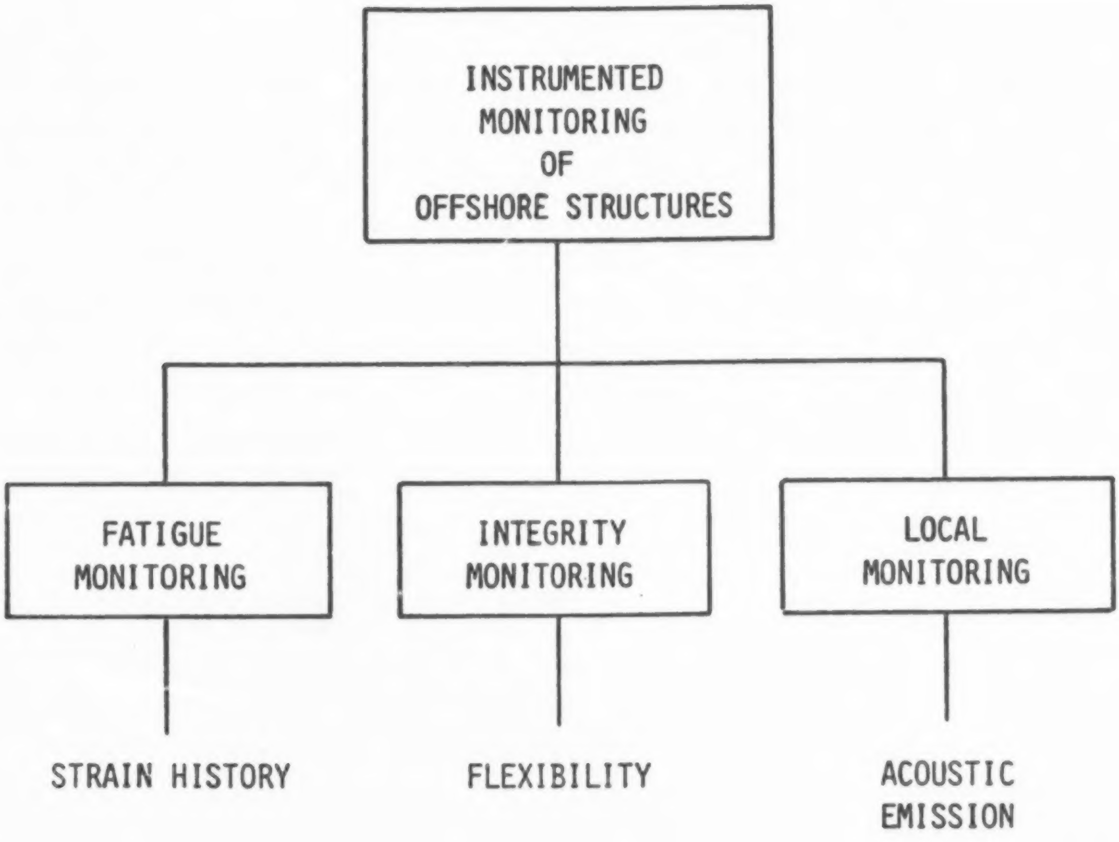

INSTRUMENTED
MONITORING
OF
OFFSHORE STRUCTURES
FATIGUE
MONITORING
INTEGRITY
MONITORING
LOCAL
MONITORING
STRAIN HISTORY
FLEXIBILITY
ACOUSTIC
EMISSION

Figure 4.4 Example of IMOS System 4.8

With the present Vibrodetection equipment (operational to a depth of about 100m) all flooded bracings can be detected. In addition, through cracks of the leg by punching (without flooding of the bracing) can be detected to 75% (ratio of external crack length to member circumference) for K-nodes and 50% for Z-nodes. An inspection using Vibrodetection does not require a cleaning procedure for bracings.

The cost to perform an inspection using Vibrodetection depends largely on the configuration of each jacket to be examined. A typical North Sea jacket with testing of 150 bracings (at about 3 bracings per hour) can cost about US $45,000 (not including travel and transportation expenses).

Tests using Vibrodetection equipment have been carried out since 1980 in the North Sea, the Persian Gulf and in Indonesia with performance of the technique reported to be satisfactory. As an example, short term repeatability (a few days) was tested on the L7C Platform in the North Sea in September 1981. Differences between successive measurements were smaller than the resolution of the measurements: i.e. less than 0.2%.

The same platform was also the object of long term stability tests. The first test, which consisted in taking reference measurements on several bracings, was carried out in September 1981. The second test took place in April 1982. This consisted of taking the same measurements and comparing them to their reference values. The variations observed were less than 2%. After further processing, it appeared that most of these variations were due to lack of frequency resolution rather than actual change in the mechanical properties of the bracings.

4.6.2 AE System Equipment

Various AE systems are currently available. One of these is the DART-32 system which features the DART (Data Acquisition in Real Time) system together with DAM (DART Activity Monitor) and CAM (Computer Analysis Monitor) of the Dunegan Corporation. The DART-32 system provides a real time display of acoustically active sources and their relative severity. The DART-32 accepts inputs from up to 32 sensors, measures relative arrival times, calculates source coordinates, and displays source information in real time on a storage display scope (CRT). In addition, the DART provides a complete event description including event amplitude, risetime, number of ringdown counts and pulse duration. Pertinent event information is reported by a 150 character-per-second teleprinter and recorded on floppy disk for future use. The DART-32 CRT provides an instantaneous display of the location of each AE event in relation to the position of the sensors (array) involved. In addition, the event attributes of amplitude, risetime, counts and pulse duration can be used in real time (or post-test) to provide plots of time history, distribution functions, and correlations with external parameters (e.g. pressure) or one of the other attributes.

The DART can be used as a stand-alone system for data acquisition, and in conjunction with a Tanberg recorder could be used to obtain information for later analysis with the CAM. The DAM can be utilized during data acquisition of the DART to monitor activity and provide limited analysis and plots of activity as a function of other analog parameters.

The DART family system prices range from US $70,000 to US $115,000 depending on options.

The Dunegan 8000 is a self-contained, single portable unit providing a maximum of 8 channels of sensor signals. The system incorporates signal processing, computer analysis, applications-oriented software, mass storage, audio monitor, and a split-screen display.

The Dunegan 8000 provide simultaneous location and monitoring of event activity and the analysis of event characteristics in real time. Analysis graphs which are available to the user include:

- total counts vs time;
- count rate vs time;
- count rate histogram;
- total count histogram;

- total event histogram;
- amplitude distribution;
- cumulative amplitude distribution;
- current event average amplitude;
- current average signal level histogram;
- parameter vs time.

Prices of the 8000 series range from US $20,000 for a minimum 2-channel system to US $55,000 for an 8-channel system will all options.

Both Dunegan systems can be used in conjunction with the Dunegan S9206 Underwater Acoustic Emission Sensors. The sensor incorporates a built-in preamplifier along with a highly sensitive element of piezoelectric material and can be used to depths of about 1000 feet.

Another acoustic emission crack monitoring (AECM) system has been developed by Syminex[4.9]. The system is built around the DART unit provided by Dunegan and an HP 1000L computer. With this system, analysis of data is not given in real time, rather, acquired data are recorded on a magnetic tape which is subsequently processed and interpreted onshore. Information obtainable from the tape includes location maps of acoustic sources, statistical data (number of events, histrograms) and conclusions on the growth of a crack.

4.6.3 Flooded Member Detection Equipment

Syminex together with Campagnie Francaise des Petroles developed Pressio-Detection for a continuous survey of all bracings of a steel jacket, by measuring the pressure in braces, which were initially pressurized, and transmitting the date to the deck by acoustic transmission.

The underwater equipment consists of a differential pressure sensor and an acoustic emitter (transducer) on each member. Therefore no cables are required. The deck equipment is built around a Hewlett Packard HP85 computer and an acoustic receiver. Values of the pressure are displayed every week on a printer. If a defect (through-thickness crack) is detected, results are displayed every four hours and alarms (warning lights) are set off.

Two offshore trials with this monitoring system yielded very good results and the system is going to be installed on a platform in Indonesian field. There are no depth limitations. Commercial cost is as yet unavailable.

5. INSPECTION ORGANIZATIONS

5.1 General

The capabilities of Canadian and foreign inspection organizations with offshore experience have been assessed on the basis of information obtained from the responses to the questionnaire as well as from interviewing the staff of a number of companies selected as to represent various aspects of offshore inspection.

5.2 Assessment Criteria

The following criteria have been adopted in assessing the selected organizations providing services related to offshore inspection:

- human resources;
- hardware resources;
- operational capabilities;
- offshore related experience.

Brief descriptions of these criteria are given below.

Human Resources

"Human resources" cover both the number and skill-level of qualified NDE operators. The criterion include divers and their ability to operate different kinds of NDE equipment.

Hardware Resources

"Hardware" refers to equipment such as atmospheric diving suits, manned submersibles and remotely operated vehicles that are used for access and support in offshore inspection work. It also covers the NDE equipment, such as detection and measuring devices available for underwater use.

Operational Capabilities

This criterion considers size, shape and location of flaws, water depth and geometric configuration of the inspection zone.

Offshore Experience

This criterion covers actual offshore related inspection experience.

5.3 Canadian Inspection Organizations

The assessment of selected Canadian organizations has been based on information presented in Table 5.1. This table presents the companies as they are formally listed in Canada. It should, however, be noted that several companies have established, or are in the process of establishing, joint ventures which should substantially enhance their capabilities. Joint ventures and their impact are further discussed in section 5.3.1, but an adequate assessment will be possible once details of these become formally available.

The assessment covers organizations that provide offshore related NDE services. There are also organizations with considerable NDE experience in, for example, the nuclear industry with potential to diversify into the offshore field. Furthermore, organizations providing equipment used for access and support in offshore inspections has also been included. Examples of such entities are Ontario Hydro, Atomic Energy of Canada Ltd. and International Submarine Engineering (I.S.E.) Ltd.

There are only few Canadian organizations with readily available resources for offshore inspection. The data retrieved must be seen in the light of the current level of offshore activity in Canada which is low compared with the North Sea and the Gulf of Mexico. Currently there are several mobile offshore units operating in the arctic waters and off the east coast. However, there are no offshore production installations (i.e. piled or gravity structures) in Canadian waters, and consequently no major scheduled underwater inspections will be required.

TABLE [illegible]

DATA ON CANADIAN INSPECTION ORGANIZATIONS

Selected Organizations	Human Resources				Hardware						
	Manpower capacity	Expertise	Skill level	Capacity break-down	Diving capacity	Underwater N.D.E. equipment		Atmospheric suits/manned submersibles		Remotely operated vehicles (ROVs)	
						No	Type	No	Inspection capabilities	No	Inspection capabilities
1) Atomic Energy of Canada Ltd.	A	CONV EC AET	E	A		-		-		-	
2) Babcock & Wilcox Canada	A	CONV	T III	C		-		-		-	
		EC	T II	B							
		FO	T II	B							
		leak testing (helium)	T III	C							
3) Bowe & Landry Inc.		CONV	E	C							
			T III	C							
			T II	A							
	A	EC	T I	C							
		TG	T -	C							
		Leak test (freon)	T -	C							
4) Can Dive Services Ltd.		UT	T II			Less than 5	UT	More	VIS	Less	VIS
	B	MPI	T -	B	DW		MPI	than	CPM	than 5	CPM (cleaning)
		RT				"	CPM	15			

TABLE 5.1 Cont'd

Selected Organizations	Human Resources				Hardware						
	Manpower capacity	Expertise	Skill level	Capacity break-down	Diving capacity	Underwater N.D.E. equipment		Atmospheric suits/manned submersibles		Remotely operated vehicles (ROVs)	
						No	Type	No	Inspection capabilities	No	Inspection capabilities
5) Can Ocean Resources Ltd.	-					-		-		Less than 5	VIS CPM
6) Coast Testing	A	CONV	E	C	-						
		"	T III	C	-						
		"	T II	B	-						
7) Eastern Technical Services Ltd.	A	CONV	E	C	-						
		"	T III	C	-						
		"	T II	B	-						
8) John T. Hepburn	C	CONV	T II	C	-						
9) Lavalin Ocean Systems Ltd.	A	CONV	E	C		Less than 5	UT	-		5-15	VIS CPM (cleaning)
		"	T II	C							
		UT	T II	C		"	MPI				
		MPI	T -	A	DW	"	CPM				
10) OIS Hanson Materials Engineering	B	CONV	E	C		5-15	UT	-		-	
		"	T II	B	-	5-15	MPI				
		EMD	-	C		Less than 5	RT				

TABLE 5.1 Cont'd

Selected Organizations	Human Resources					Hardware					
	Manpower capacity	Expertise	Skill level	Capacity break-down	Diving capacity	Underwater N.D.E. equipment		Atmospheric suits/manned submersibles		Remotely operated vehicles (ROVs)	
						No	Type	No	Inspection capabilities	No	Inspection capabilities
11) Oilfab Haltech Ltd.	A	CONV EC	E T III T II	C C B	- - -	-		-		-	
12) Ontario Hydro	B	CONV AET FO PD PR TOM	E T II	B C							
13) Research & Productivity Council (RPC)	B	CONV AET EC PD PR TG	E T III T II	C C B	- - -	Less than 5	UT	-		-	
14) Rig Inspection & Repair Services	C	EMD	T	C	-	Less than 5	EMD				

TABLE 5.1 Cont'd

Selected Organizations	Human Resources					Hardware					
	Manpower capacity	Expertise	Skill level	Capacity break-down	Diving capacity	Underwater N.D.E. equipment		Atmospheric suits/manned submersibles		Remotely operated vehicles (ROVs)	
						No	Type	No	Inspection capabilities	No	Inspection capabilities
15) Stasuk Testing & Inspection Ltd.	B	CONV	E	C	-	Less than 5	UT	-		-	
		"	T III	C	-						
		"	T II	B	-						
		UT RT MPI	T II	C	DW	5-15	RT				
16) Techno Scientific Inc.	A	CONV	E	B	-	-		-		-	
			T III	C	-						
		EC									
17) The NDE Service Group Inc.	A	CONV "	E T III	C							
		"	T II	A							
		MPI	T -	C	SW						
		UT	T II	C	SW						
18) T.J. Inspection Services	C	RT UT MPI	T II T I T	C	DW	-		-		-	
19) Trutom	B	CONV	E	C	-	-		-		-	
		"	T III	C	-						
		"	T II	B	-						

TABLE 5.1 Cont'd

Selected Organizations	Human Resources					Hardware					
	Manpower capacity	Expertise	Skill level	Capacity break-down	Diving capacity	Underwater N.D.E. equipment		Atmospheric suits/manned submersibles		Remotely operated vehicles (ROVs)	
						No	Type	No	Inspection capabilities	No	Inspection capabilities
20) Warnock Hersey Professional Services Ltd.		CONV	T III	C	-	-		-		-	
	B	"	T II	B							
21) Wolf Sub Ocean Ltd.		CONV	E	C	-	Less than 5	UT	Less than 5	VIS CPM	Less than 5	VIS CPM (cleaning)
	B	UT	T I	B	DW		MPI				
		MPI	T	B	DW	"	CPM				

Legend to TABLE 5.1:

Type of NDE Personnel:	E:	Engineers with NDE qualifications (metallurgical, electrical etc.)
	T:	NDE Technicians
Capacity ranking:	A:	more than 15
	B:	5 to 15
	C:	less than 5
Techniques:	AET:	Acoustic Emission Testing
	AH:	Acoustic Holography
	AMR:	Acceleration/Movement Recording
	CONV:	Conventional Methods (i.e. RT, UT, MPI)
	CPM:	Cathodic Potential Measurement
	EC:	Eddy Current
	EMD:	Electro Magnetic Detection
	FO:	Fibre Optics
	MPI:	Magnetic Particle
	PD:	Potential Drop
	PR:	Plastic Replica
	RT:	Radiographic Testing
	SGT:	Strain Gauge Technique
	TG:	Thermography
	TOM:	Tomography
	UT:	Ultrasonic Testing
	VIS:	Visual Inspection

Legend to TABLE 5.1 Cont'd

Level:	I:	Basic qualification. The operator has theoretical but virtually no practical experience. Will be able to interpret results under supervision by level II and III personnel.
	II:	Has both theoretical and practical experience and can operate and interpret on his own.
	III:	Has level II and minimum of 1 years experience plus additional exam.
Diving:	SW:	Shallow water (less than approx. 40m)
	DW:	Deep water (less than approx. 300m)
	HW:	Hyperdeep water (larger than 300m)

The methodology used here for data compilation and assessment is aimed at easy updating in anticipation of significant changes in the capabilities of Canadian inspection organizations in response to the construction of production installations.

5.3.1 Assessment of Canadian Organizations

The assessment of Canadian organizations is reflected in Table 5.2. Despite the numerical ranking in the table, this should not be interpreted as an absolute quantitative measure of the organizations. The ranking merely provides a basis for comparison and is subject to the information made available at the time of assessment.

Companies that are not directly involved in performing NDE, but have special capabilities related to this field (e.g. structural monitoring, manufacturing of equipment etc.) are not included in the table as they constitute a special category.

The total scores shown in column 5 confirm that few organizations currently have the combined resources necessary to perform major underwater inspection. However these are organizations with significant potential capabilities. The contents of the table should be viewed in the light of the following observations:

- (Column 1) In terms of human resources the diver-inspector is a most valuable asset to a company providing NDE services, as the combined skills are essential for several types of underwater inspection. However, satisfactory NDE results may in some cases be obtained by using divers with no NDE skill. This will also apply to the use of ROVs. Successful inspection here is mainly a function of the supervision quality, crews' qualifications and experience, as well as operation planning.
- (Column 2) The ranking in column 2 is based on the fairly limited number of underwater NDE (monitoring, detection) units presently available in Canada. The majority of the existing units consist of MPI, CPM and equipment for RT. Underwater UT is so far mainly performed by a modified shear or compression probe with surface readout. However, underwater NDE units used in conventional inspection techniques are already available on the market, or they may be produced by the modification of the in-house equipment.

TABLE 5.2

ASSESSMENT OF CANADIAN OFFSHORE INSPECTION ORGANIZATIONS

Assessment Criteria Organizations	Human Resources (1)	Hardware Resources (2)	Operational Capabilities (3)	Offshore Related Experience (4)	Total Score (5)
1) Atomic Energy of Canada Ltd.	3	1	1	1	6
2) Babcock & Wilcox Canada	3	1	1	1	6
3) Bowe & Landry Inc.	3	1	1	1	6
4) Can Dive Services Ltd.	3	2	3	2	10
5) Can Ocean Resources Ltd.	2	1	1	2	6
6) Coast Testing	2	1	1	1	5
7) Eastern Technical Services Ltd.	2	1	1	1	5
8) Hepburn Ltd.	1	1	1	1	4

TABLE 5.2 Cont'd

Assessment Criteria	Human Resources	Hardware Resources	Operational Capabilities	Offshore Related Experience	Total Score
Organizations	(1)	(2)	(3)	(4)	(5)
9) Lavalin Ocean Systems Ltd.	3	2	3	2	10
10) OIS Hanson Materials Engineering Ltd.	3	2	1	2	8
11) Oilfab Haltech Ltd.	3	1	1	1	6
12) Ontario Hydro	3	1	1	1	6
13) Research & Productivity Council	3	1	1	1	6
14) Rig Inspection & Repair Services	2	1	1	1	5
15) Stasuk Testing & Inspection Ltd.	3	2	2	2	9
16) Techno Scientific Inc.	3	1	1	1	6

TABLE 5.2 Cont'd

Assessment Criteria Organizations	Human Resources (1)	Hardware Resources (2)	Operational Capabilities (3)	Offshore Related Experience (4)	Total Score (5)
17) The NDE Service Group Inc.	3	1	2	1	7
18) T.J. Inspection Services	2	1	2	1	6
19) Trutom Ltd.	2	1	1	1	5
20) Warnock Hersey Professional Services Ltd.	2	1	1	1	5
21) Wolf Sub Ocean Ltd.	3	2	3	2	10

Total actual and potential capabilities have been rated on a scale 1-4, to indicate the following:

4 - outstanding
3 - good
2 - fair
1 - inadequate

The number of ROVs currently in use is fairly limited regarding their inspection capabilities. It should however be noted that considerable capabilities in the design and manufacturing of custom built ROVs have been identified at International Submarine Engineering Ltd. (ISE). In addition to the more traditional "eyeballs" (i.e. visual inspection by video or still photo) and CPM readings, ISE produces more sophisiticated units that will clamp themselves to the structure and use manipulator arms for inspection. Such a robot was custom built in 1983 to perform normal probe ultrasonic wall thickness measurements, magnetic particle crack detection and potential measurements; it is also equipped with a high pressure surface cleaning device in addition to advanced photo/video equipment. This unit was designed and assembled in Canada for a foreign underwater service organization and is now used for inspection of a couple of fixed jacket structures in the Gulf of Mexico in about 300m of water.

- (Column 3) The operational capabilities are a function of human resources, hardware and relevant experience. As previously mentioned, the ROVs as well as the manned submersibles now in use have very limited NDE capabilities and depend heavily on diver support in order to perform NDE underwater. This may change with the development of remotely operated systems. However, the operation of such equipment requires skills that can only be obtained through extensive training and experience. It appears that the combination of the necessary equipment and skills for doing advanced remotely operated testing is not currently available. This is borne out by the fact that advanced ROVs are used only for video and still photo in other offshore theatres.

  The ranking in column 3 reflects the comparative resources in terms of NDE operator-divers and underwater equipment.

- (Column 4) There are understandably no Canadian companies with extensive offshore experience. However, attempts have been made and are continuing to transfer technology and experience from other offshore theatres through joint ventures. Therefore it should be noted that the assessment of, for example, OIS

Hanson Materials Engineering Ltd., has taken into consideration the advantage of access to Oilfield Inspection Services' (Aberdeen, UK). There might be other similar arrangements, but these joint ventures not formally established or in the process of being established could not be included here as no reliable and authoritative information was available. However the situation with regard to join ventures is in a state of flux and should be continually mentioned.

- (Column 5) The scores in column 5 are meant to indicate the organizations' current and potential capabilities. The companies listed range from large organizations (e.g., Lavalin Ocean Systems Ltd.) to small, recently established, companies (e.g. T.J. Inspection Services). This will significantly affect the capacity for inspection work. However, the expected volume of inspection in Canadian waters is not likely to require such capacities as are required in the North Sea or the Gulf of Mexico.

The evaluation of capabilities for instrumented structural monitoring is beyond the scope of this study and is not therefore included. However this is attracting much interest, particularly for harsh environments and deep waters. For example, due to the increased activities in the arctic and the need to assess ice forces and behaviour of ships and installations, structures in ice have been extensively instrumented. The current state-of-the-art is concerned mainly with the assessment of forces and structural response, and not with surveillance for monitoring of defects.

In addition to the "traditional" strain gauges and accelerometers for assessment of forces and response, fatigue gauges have been installed on icebreakers. This equipment may be of particular interest in assessing structural integrity of certain critical areas on offshore installations, and has been used on structures in the Gulf of Mexico.

It should be noted that considerable expertise in structural monitoring have been identified at Weir Jones Engineering Consultants Ltd.

5.4 Foreign Inspection Companies

There are of course many inspection organizations worldwide supplying offshore NDE services. Based on a review of organizations in America, Japan and Europe a representative number of organizations have been identified to reflect the state-of-the-art in the provision of underwater NDE services. These companies, which are listed in Table 15 were assessed on the basis of information obtained on both the quantity and quality of human resources, hardware capabilities and actual offshore experience. There may well be other companies that are not listed but can offer comparable NDE services. However their inclusion would not qualitatively impact the state-of-the-art assessment.

5.4.1 Assessment of Foreign Inspection Companies

The assessment of the companies listed in Table 5.3 is subject to the following observations:

- the predominantly equal and relatively high ranking indicates that these companies are capable of providing NDE services for major offshore installations as is evident from their reference projects in the table. This fact places them in the same league, although a more refined assessment would most probably reveal some differences;

- the companies have a significant number of qualified NDE personnel on the staff and can also draw on the pool of freelance diver-inspectors at short notice, so that they can readily mobilize at least 50 diver-inspectors;

TABLE 5.3
ASSESSMENT OF FOREIGN OFFSHORE INSPECTION ORGANIZATIONS

Assessment Criteria Organizations	Human Resources	Hardware Resources	Operational Capabilities	Major Offshore Projects	Total Score
Comex Houlder Diving Ltd. Aberdeen UK	4*	4	4	Brent Field UK 4	16
Oceaneering International Services Aberdeen UK	4	4	4	Hutton UK Valhall Norw 4	16
Oilfield Inpsection Services Aberdeen UK	4	4	4	Statfjord Norw Brent UK 4	16
Seaway Diving-Stolt Nielsen Oslo, Norway	4	4	4	Ekofisk Norw 4	16
SubSea Offshore Ltd. Aberdeen UK	4	4	4	Ninian UK Magnus UK 4	16
Thalassa Offshore (Scotland) Ltd. Aberdeen UK	4	4	4	Brent UK Brunai 4	16
Wharton Williams Taylor Aberdeen UK	4	4	4	Statfjord Norw Beryl UK 4	16

* 4 - outstanding
3 - good
2 - fair
1 - unsatisfactory

- the majority of the divers are skilled in MPI and ultrasonic compression probe technique. For the more complex shear wave angle probe technique which requires, for example, CSWIP 3.6* qualification, the number of divers available worldwide are limited and each company can call on the services of about 10 highly qualified divers;

- the companies can offer expertise in all the commonly used NDE techniques but their experience has been mostly in visual inspection (e.g. still photo, closed circuit television), magnetic particle inspection and ultrasonic testing;

- despite their average total capacity being almost equal, some of the companies are outstandingly resourceful in specific areas. For example, Oceaneering International together with their recent acquisition of Solar Ocean System, and Suboffshore have from 30-50 ROVs; but Oceaneering can mobilize the largest number of divers (about 2000), as well as 20-30 atmospheric suits and manned semisubmersibles in peak periods;

- the NDE services performed by the companies include the collection, processing and presentation of data. In this area Suboffshore Ltd. and Thalassa have considerable development work in progress and claim to offer exceptionally good hard copy records of MPI Testing, as well as computerized processing and results presentation;

- it would appear that most companies tend to modify the equipment currently available to suit specific applications and market them. For example, Oilfield Inpsection Services produce and market their own OIS MKII MPI unit, underwater ultrasonic repeating system MKII and Nautilus radiography unit.

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* CSWIP is the acronym for Certification Scheme for Weldment Inspection Personnel used in the U.K. 3.6 is the highest level in this scheme.

6. CONCLUDING REMARKS AND RECOMMENDATIONS

The non-destructive evaluation of an offshore structure is performed to assess the fitness of the structure to continue fulfilling its functions safely. The evaluation is commonly based on the results of inspection which is carried out periodically or in response to damages sustained by the structure. It should be stressed that the timely detection and repair of structural defects and damage can significantly contribute to the prevention of major offshore catastrophies or the disruption of production.

Experience shows that the main defects encountered in inspection are cracks and corrosion, and that a type III inspection is most critical for meeting the principal objectives of non-destructive evaluation. Methods that are currently used for type III are:

- close visual inspection by divers;
- radiography (gamma-ray, x-ray);
- ultrasonic testing;
- magnetic particle inspection.

NDE methods based on ultrasonics have been found in general to be suitable for underwater use and recommended for the examinations of internal defects and wall-thickness measurements where the velocity of sound propagation through the material under examination is known. Various methods based on the principles of electromagnetism have also proved useful in the underwater detection of surface defects.

Our survey shows that the common practice in equipment development is the modification of what has been successfully used above water to make it operational underwater.

The survey reported in this study indicates that some operators claim that few defects have actually been detected in planned type III inspection. Undoubtedly the reliability and quality of offshore inspection should be improved. The standards of documentation of inspection reports and repeatability of observations have been identified to require upgrading. Aids for visual inspection should also be improved.

It is evident from the evaluation of NDE organizations that considerable expertise in NDE and offshore inspection has been accumulated in major offshore areas such as the North Sea. There is also NDE expertise in Canada which forms a base for both the transfer of the latest NDE technology and the development of new techniques and equipment.

The review of the NDE techniques under development indicates that the emphasis will increasingly be an automation and the remote control of equipment, as well as on real time signal processing and the optimization of the operations involved in offshore NDE. The development of such new techniques as ultrasonic holography and computerized tomography are still in the experimental stage and cannot therefore be assessed on the basis of performance in real offshore situations. However, as discussed in Section 3 encouraging results have been obtained during the development of these and other novel techniques.

The instrumented monitoring of offshore structures (IMOS) has been discussed in section 4 for it closely relates to and complement NDE. One significant advantage of continuous monitoring made possible by IMOS, in contradistinction to periodic inspection, is that monitoring would not interfere, at least to any significant degree, with the normal operations on the platform. Furthermore the information obtained from IMOS will provide a most valuable feed-back to test design assumptions. For structures in water depth range of 70-150m IMOS can complement diver inspection, whereas in deeper waters it can be used with ROVs.

On the basis of the present study the following recommendations are proposed for the consideration of CANMET:

- the in-service inspection should be an integral part of the overall safety assessment of offshore installations;

- the criteria for periodic type III inspection should be critically reviewed and rationalized;
- the reliability and feasibility of techniques not regularily applied in underwater inspection such as acoustic emission testing, ultrasonic-time-of-flight and techniques based on electromagnetic changes should be assessed;
- rigorous procedures for documentation and independent verification of recorded observations should be established;
- in view of the harsh environment in which inspection data is acquired, and several examples of unsatisfactory reliability of underwater defect detection, emphasis should be put on the development of semiautomatic and fully automatic underwater NDE systems; this should include further improvements of manipulator arms for ROVs;
- the rough operational conditions offshore and the rather frequently occuring delays reported due to equipment breakdown focus on the need for procedures which would ensure thorough checking of equipment prior to use, and stricter equipment specifications aiming at improved reliability;
- high quality still photos and video recording are extremely valuable and underwater CCTV Systems using high-resolution cameras with magnifying options should be further developed;
- procurement of equipment for laboratory investigation is not deemed to be a priority in Canada. In view of the NDE hardware currently in use, or being developed, it would seem that further investment at this point in time is not warranted;
- provision of incentives for implementation of training programs, perhaps through joint-ventures between Canadian and foreign companies, should be considered. Such joint-ventures that effectively transfer the technology to Canada on a permanent basis should be encouraged and supported. The government can be an effective instrument is implementing training programs;
- monitoring of on-going research and possibly buying into research and development projects that are being currently carried out are considered to be potentially valuable. Canada should of course participate in the development of advanced methods and equipment for NDE equipment, once the most promising ones have been identified in the light of the findings of current research and development work.

7. ACKNOWLEDGMENT

This work was performed for the Physical Metallurgy Research Laboratories, CANMET, Energy Mines and Resources Canada under Supply and Services Canada Contract no. OSQ83-00035. The authors acknowledge the support received from Dr. D. Mak, PMRL, in the scientific administration of the contract.

8. DISCLAIMER

Unless referenced, any data presented, opionions, findings, conclusions, or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of CANMET.

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9. REFERENCES AND BIBLIOGRAPHIES

9.1 References

1.1 Bosselar, H.; "The State of the Art of Underwater Inspection". European Petroleum Conference, 1982, Paper No. 334.

1.2 U.K. Statutory Instrument No. 289, Offshore Installations (Construction and Survey). Regulations 1974.

1.3 Offshore Installations: Guidance on the Design and Construction. U.K. Department of Energy, 1977.

1.4 Guidelines for the Inspection of Primary and Secondary Structures of Production and Shipment Installations and Underwater Pipeline Systems. Norwegian Petroleum Directorate, 1977.

1.5 Enforcement of Article 34 of the Mining Regulations for the Continental Shelf and Article 36d of Mining Regulations 1964 for fixed Installations. Dutch Mining Directorate, 1978.

1.6 Newfoundland Regulation 183/82. The Offshore Installations (Design, Construction and Survey) Regulations, 1982.

2.1 Lumb, R.F. and Winship, P.; "Magnetic Particle Crack Detection". Part 1, Metal Construction, 1977, 9, 7, pp. 293-296. Part 2, Metal Construction, 1977, 9, 8, pp. 331-334.

2.2 Auchterlounie, A.J.; "Magnetic Particle Inspection Underwater - The True Potential". Journal of the Society for Underwater Technology, 8, 3, 1982, pp. 17-20.

2.3 "Non-Destructive Testing, Principles and Limitations". Veritas Training Center, January 1983.

2.4 Walther, K.G.; "The Magfoil Method". Materials Evaluation, April 1983.

2.5 Stumm, W.; "Magnetographic Weld Inspection System for Underwater Installations". Materials Evaluation, April 1983.

2.6 Zeller, R.; "Risstiefenmessung nach dem Potentialsondenverfahren mit Wechselstrom". Materialpruef, 23, 3, 1981.

2.7 Haugen, R. and Rangnes, E.; "A New Instrumentation for Fatigue Crack Depth Measurement with A.C. Potential Drop Technique". Second European Conference on Non-Destructive Testing, Wien, 1981, Veritas Paper No. 81 P050.

2.8 Moncaster, M.B.; "Underwater Inspection of Welds - An Assessment of Some Techniques and Their Reliability". Journal of the Society for Underwater Technology, 8, 3, 1982, pp. 7-12.

2.9 Sletten, R.; "Prerequisites of Effective Inspection in Light of Recent Experiences from the North Sea". Veritas Paper No. 81 P004, January 1981.

2.10 Dalberg, P., Haugen, R. and Myrhaug, O.; "Crack Depth Determination - The AC - Potential Drop Technique". Veritas Technical Report: 81-1079, November 1981.

2.11 Mudge, P.J. and Williams, S.; "Performance of Ultrasonic Nondestructive Methods for Defect Assessment in Relation to Fracture Mechanics Requirements". Fitness for Purpose Validation of Welded Constructions, London, 1981, Paper No. 44.

2.12 Foerli, O. and Pettersen, B.; "Reliability of Ultrasonic and Radiographic Testing". Fitness for Purpose Validation of Welded Constructions, London, 1981, Paper No. 27.

2.13 Singh, A., McClintock, R.; "Computer-Controlled System for Nondestructive Thickness Measurement of Corroded Steel Structures". Journal of Energy Resources Technology, Vol. 105, December 1983.

2.14 Hoegmoen, K. and Veierland, S.E.; "Corroscan - An Automated Ultrasonic Equipment for Corrosion Inspection". International Conference on Pipeline Inspection, June 1983, Edmonton, Canada.

2.15 Dalgliesh, E.H., Casswell, P.H. and Poole, M.J.; "The Ultrasonic Torch - A Novel Device for Monitoring Steel Structures Underwater". Offshore Technology Conference, 1982, Paper No. 4362.

2.16 Foerli, O., Hansen, B., Sanberg, S., and Aastroem, T.; "A Comparison of Radiographic and Ultrasonic NDE, Pilot Study of a Statistical Model for Evaluation of Examination Performance". The Danish Welding Institute, Nordtest Project 72-76, March 1978.

2.17 Foerli, O.; "Comparison of Radiography and Ultrasonic Testing". Second Nordiske NDT Symposium, Copenhagen, May 1979.

2.18 Kristiansen, O. and Sletter, G.I.; "Diverless Underwater Inspection Program (DUIP)". Remotely Operated Vehicle Conference 1983, California.

3.1 Hawker, B.M.; "The Automation of Inspection of Thick Steel Sections Using the Ultrasonic 'Time-of-Flight' Technique". OECD/IAEA Specialist Meeting on Defect Detection and Sizing, Ispra, Italy, May 1983.

3.2 Singh, G.P., Cervantes, R.A., and Spinks, R.L.; "Ultrasonic NDE Technique for the Examination of Low-pressure Turbine Disk Rims". Materials Evaluation, Vol. 41, December 1983.

3.3 Gebhardt, W., Bonitz, F. and Woll, H.; "Defect Reconstruction and Classification by Phased Arrays". Materials Evaluation, 40, 1, 1982.

3.4 Hoeller, P., et al; "Non-Destructive Ultrasonic Techniques for Classification and Reconstruction of Defects". Fraunhofer-Institut fuer zerstoerungsfreie Pruefverfahren.

3.5 Holographic Non-destructive Testing. Edited by R.K. Erf, Academic Press, New York, 1974.

3.6 Smith, K.T., Solmon, D.C. and Wagner, S.L.; "Practical and Mathematical Aspects of the Problem of Reconstructing Objects from Radiographs". Bulletin of American Mathematical Society, 23, 6, 1977.

3.7 Minerbo, G.; "MENT: A Maximum Entropy Algorithm for Reconstructing a Source from Projection Data". Computer Graphics Image Processing, 10, 1, 1979.

3.8 Kruger, R.P. and London, J.R.; "The Industrial Use of Filtered Back Projection and Maximum Entropy Reconstruction Algorithms". Materials Evaluation, 40, 12, 1982.

3.9 Watson, J.; "Holography - Can it be Used Underwater?". Journal of the Society for Underwater Technology, Winter 1981.

3.10 Stankoff, A.G. and Collins, D.H.; "Application of Acoustical Holography to the Inspection of Offshore Platforms". Offshore Technology Conference, 1978, Paper No. 3332.

4.1 Silk, M.G., et al.; "The Continuous Monitoring of Fixed Offshore Platforms for Structural Failure". A Review and Assessment of Techniques. AERE, HARWELL, 1975, R8055.

4.2 Vandiver, J.K.; "Structural Damage Detection by Measurement of Dynamic Response". SNAME Paper T4-3, 1977.

4.3 Lenain, J.C.; "General Principles of Acoustic Emission". Materials Evaluation, 39, 11, 1981.

4.4 Scruby, C.B. and Wadley, H.N.G.; "An Assessment of Acoustic Emission for Nuclear Pressure Vessel Monitoring". Progress in Nuclear Energy, 11, 3, 1983.

4.5 Dunegan, H.L.; "Acoustic Emmission - New Inspection Technique". Offshore Technology Conference, 1977, Paper No. 2851.

4.6 Bartle, P.M.; "Acoustic Pulsing - A Technique for Remote Defect Monitoring". The Welding Institute Research Bulletin, September 1983.

4.7 Brown, D. and Benett, A.; "NDT Techniques Often Unreliable". Offshore Engineer, May 1981.

4.8 Liland, H. and Flogeland, S.; "IMOS - Instrumented Monitoring of Offshore Structures". Offshore Goeteborg, 1983.

4.9 Lepert, P.; "Acoustic Emission Crack Monitoring System; General Presentation". Societe Syminex.

9.2 Det norske Veritas Bibliography

- Underwater Technology, Veritas' Research and Development Projects for 1984.
- Karlsen, F.; "Codes and Standards NDT - Acceptance Criteria". Veritas' course on Field Inspection, Lecture No. 48.
- Sletten, R.; "Underwater Inspection, Maintenance and Repair on Offshore Structures and Pipelines - Technical Aspects". IOR General Meeting, Vlaardingen, January 1978, Paper No. 78-0022.
- Sletten, R. and Eriksen, H.; "Improving the Efficiency of Inspection and Maintenance: The Strategy of Periodic Maintenance".
- Foerli, O.; "Non-Destructive Testing Under Water". Paper No. 83 P002, June 1983.
- Sletten, R. (DnV), Ringard, M. and Torsen, H.O. (Continental Shelf Institute); "Trends in Underwater Operations with Special Reference to Inspection and Repair of Offshore Installations".
- Sletten, R.; "Underwater NDT - A Tool for Offshore Maintenance and QA". Second Nordiske NDT Symposium, Copenhagen, May 1979.
- Foerli, O.; "Inspection Methods - Equipment, Application and Development, Conference on Inspection and Condition Monitoring of Fixed Marine Constructions". Norway, January 1982.
- "Offshore Inservice Inspection and Monitoring - A Basis for Efficient Operation and Maintenance", Veritas Conference, November 1979, Hoevik, Norway.
- Dalberg, P.; "A Four Probe Technique for Accurate Sizing using Ultrasonic Diffraction", Paper No. 81 P105, November 1981.

- Hoegmoen, K. and Haugen, R.; "A New Ultrasonic Wheel Probe". Paper No. 81 P052.

- Hansen, O.K., Foerli, O. and Rangnes, E.; "Automatized Ultrasonic Equipment for Underwater Corrosion Inspection". Paper No. 80 P049.

- "Veritas' Underwater Trials Area (UWTA)". January 1980.

- "Underwater Testing and Training - Brief Introduction to Testing and Training Possibilities", December 1981, Bergen, Norway.

- "Qualifying Underwater Inspectors". VERITAS, No. 106-Oslo-1982-II.

- "Internal Corrosion Monitoring". VERITAS, No. 106-Oslo-1982-II.

- "ROVs for Underwater Inspection". VERITAS, No. 106-Oslo-1982-II.

- Skarsaeterhagen, A.; "R & D Project: Certification Scheme for Welding Inspectors". Veritas Report No. 83-0826, 1983.

- Moeller, O. and Bragaa, O.; "Comments on the Applicability and Qualification of UT-Operators According to API RP 2X and Specification D003-N-SS-005". March 1983.

- Hatlo, J.; "Application of Underwater Testing". British Journal of Non-Destructive Testing, 21, 6, 1979.

- Walter, J.C., Valland, G. and Onsvaag, E.; "New Trends in the Application and Evaluation of Non-Destructive Testing". International Conference on Quality Control and Non-Destructive Testing in Welds, London, England, 1, 1974.

- Saebjoernsen, K. and Foerli, O.; "Underwater NDE Technique". Materials Evaluation, April 1983.

- Det norske Veritas, Rules for the Design, Construction and Inspection of Offshore Structures, Appendix I, 1977 (with corrections 1981).

- Det norske Veritas, Technical Note A 801, Approval of Underwater Inspection Procedures, 1983, Rev. 0.

- Det norske Veritas, Technical Note A 802, Certification of NDE Equipment for Underwater Inspection, 1983, Rev. 0.

- Det norske Veritas, Technical Note A 803, Qualification of Underwater Inspection Personnel, 1983, Rev. 0.

9.3 General Bibliography

- International Institute of Welding; "Information on Common Practices for Underwater Non-Destructive Testing". DOC. V-745-83, June 1983.

- Farley, J.M. and Dikstra, B.J.; "Review of the Basic Capabilities and Limitations of NDT Techniques Used for Inspection of Offshore Structures". European Petroleum Conference, 1982, Paper No. 333.

- Youshaw, R. and Dyer, C.; "Underwater Non-Destructive Testing of Ship Hull Welds". Ship Structure Committee, U.S. Coast Guard Headquarters, September 1979, Paper No. SSC-293.

- Amiot, P.; "Inspection and Performance of Underwater Welds". International Institute of Welding Annual Assembly, Underwater Welding Conference, Trondheim, Norway, June 1983.

- "Eddy Current Detector". Underwater Systems Design, June/July 1981.

- The Welding Institute; "CP/E/1341 - Optimised Magnetic Particle Inspection Techniques for Welded Joints". May 1983, London, England.

- Silk, M.G.; "The Transfer of Ultrasonic Energy in the Diffraction Technique for Crack Sizing". Ultrasonics, May 1979.

- Lovell Smith, A.; "Underwater Visual Inspection". Journal of the Society for Underwater Technology, 8, 3, 1982, pp. 5-6.

- Munro III, J.J.; "Gamma Ray Sources for Industrial Radiography". C.S.N.D.T. Journal, 3, 4, 1982.

- Certification Scheme for Weldment Inspection Personnel, Document No. CSWIP-DIV-7-83, 2nd Edition, 1983.

- Aastroem, K.T.; "The Nordtest Certification Scheme for NDT-Personnel". 10th World Conference on Non-Destructive Testing, pp. 211-217.

- Duffy, D.E.; "Underwater Inspection: Theory and Practice". Potter, N.; Heyden and Son Ltd., London, 1981.

- Webborn, T.J.C.; "Systems for Inspection and Remote Crack Detection". Oceanology International 80 Proceedings, 1980, pp. 26-31.

- Allen, K.P.; "Further Considerations for NDT Validity and Structural Integrity". Offshore Inspection Repair and Maintenance Proceedings 1981.

- American Petroleum Institute Recommended Practice for Ultrasonic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Ultrasonic Technicians, Recommended Practice API RP 2X, 1980.

- Collins, H.D. et al.; "Acoustical Holography Matrix Array Imaging System for the Underwater Inspection of Offshore Oil Platform Weldments", Acoustical Imaging, 8, 8th International Symposium, 1978.

- King, M.J.; "Search Continues for Faster Detection Equipment". Offshore Oil Weekly, July 1980.

- "Ultrasonic Technique Speeds Crack Detection", Gas World, July 1982, pp. 7.

- Mittleman, J. and Wyman, D.B.; "Underwater Inspections: Credibility and Technology", Offshore Technology Conference, 1981, 2, pp. 207-210.

- MacLeod, C.J., Pearson, J. and Hayward, G.; "Processing Techniques for the Inspection of Offshore Structures". Conference on Acoustical Speech Signal Processing, 2, 1981.

- Browne, R.D., Doyle, V.J. and Papworth, F.; "Inspection and Repair of Offshore Concrete Structures", European Petroleum Conference, 1980, Paper No. 220.

- Rodriques, P.E.L.B., Wong, W.K. and Rogerson, J.H.; "Weld Defect Distributions in Offshore Platforms and Their Relevance to Reliability Studies, Quality Control and In-Service Inspection". Offshore Technology Conference, 1980, Paper No. 3693.

- Allen, K.P.; "Underwater NDT - Problems and Solutions", World Conference on Non-Destructive Testing, 1979, Paper No. 2A-13.

- Busby, R.F.; "Underwater Inspection/Testing/Monitoring of Offshore Structures", Ocean Engineering, 6, 4, 1979.

- Stumm, W.; "Magnetic Stray Flux Techniques in Non-Destructive Testing - Theory, Application, New Developments". British Journal of Non-Destructive Testing, 21, 4, 1979.

- Edwards, W.R. and Hargreaves, D.M.G.; "Five Year Underwater Inspection Program of a North Sea Steel Platform Jacket". Offshore Technology Conference, 1, 1979.

- Jackson, H.; "New Ultrasonic Tool Checks Offshore Pipeline Welds". Oil and Gas Journal, 76, 11, 1978, pp. 78.

- McEwan, W.; "NDT and the Underwater Environment". British Journal of Non-Destructive Testing, 20, 1, 1978, pp. 18-20.

- Peters, V.A.; "Offshore Platform NDT Instrumentation Requirements". Institute of Physics Conference, London, England, 34, 1977, pp. 13-18.

- 8th World Conference on Non-Destructive Testing, 1976.

- Browne, R.D., Domone, P.L. and Geoghegan, M.P.; "Inspection and Monitoring of Concrete Structures for Steel Corrosion". Offshore Technology Conference, 1977, Paper No. 2802.

- Goodfellow, R. and Bourne, M.J.; "Underwater Inspection of Deep Water Facilities", Petroleum Engineer, 48, 7, 1976, pp. 11-12.

- Alia, B.L., Wheatcroft, M.F. and Null, C.L.; "Material Selection, Welding and Non-Destructive Testing Guidelines for Offshore Mobile Drilling Units". Offshore Technology Conference, 1976, Paper No. 2647.

- Peters, V.A., Davies, D.M. and Hughes, B.G.; "Role of Non-Destructive Testing in the Offshore Oil and Gas Industry". Weld in Offshore Constructions Conference, 1974, 1, pp. 205-213.

- Silk, M.G., Williams, N.R. and Bainton, K.F.; "Potential Role of NDT Techniques in the Monitoring of Fixed Offshore Structures". British Journal of Non-Destructive Testing, 17, 3, 1975, pp. 83-87.

- Lawton, T.R.; "Inspection of Underwater Structures", Petroleum Review, 24, 288, 1970, pp. 393-395.

- Hung, Y.Y. and Grant, R.M.; "Non-Destructive Testing of Offshore Structures by Shearography", Behaviour of Offshore Structures, Vol. 2, Hemisphere Publishing Corp., 1982.

- Herve, J.L., Ling, M.T.S. and Undeli, J.; "Frigg Pipeline System uses New Inspection Techniques". Pipeline Industry, March 1982.

- "NDT Adapted for Underwater Use". J. Inst. Eng. Aust., August 1980.
- Rogers, L.M., Hansen, J.P. and Webborn, T.J.C.; "Application of Acoustic Emission Analysis to the Integrity Monitoring of Offshore Steel Production Platforms". Materials Evaluation, August 1980.
- Rutherford, P.; "Inspection, Repair and Maintenance Offshore - What are the Training Requirements". Jernindustri, November 1979.
- Edwards, G.R.; "Ultrasonics in the North Sea Oil Industry", Anticorros. Methods Mater., December 1979.
- Mittleman, J.; "Underwater Ship Hull Inspections". Gateway to NDT Technology, American Society for NDT, 1979.
- Muir, G.; "Certification for In-Water Survey and Inspection". British Journal of Non-Destructive Testing, September 1979.
- Britton, C.F.; "Monitoring of Internal Corrosion in Offshore Installations". Mar. Eng. Rev., January 1979.
- Stankoff, A.G. and Collins, D.H.; "Application of Acoustical Holography to the Inspection of Offsore Platforms". Offshore Technology Conference, 1978, 4.
- "Underwater Inspection - Offshore Structures", Weld. Des. Fabr., September 1977.
- ONeill, T.J.; "Underwater Inspection by Divers", Proc. Conf. on Long Service from Offshore Structures, 1976.
- Sansom, W.H.; "Non-Destructive Testing, Pt. 6, Underwater NDT Techniques". Welder, 40, 193, pp. 16-18.

- Jones, H.W. and Miles, H.T.; "Development of Ultrasonic Image Converters for Underwater Viewing and Other Applications". Ocean Engineering, July 1969.

- Junke, H.; "Underwater Wall-Thickness Measurements and Weld Testing by Ultrasonics". 5th International Conf. on Non-Destructive Testing, Ottawa, Canada, 1969.

- Lambert, G.; "An Application of Underwater Radiography". Materials Evaluation, March 1968.

- Atteraas, L., et al.; "Underwater Technology - Offshore Petroleum, Pergamon Press, 1980.

- "Magnetic Particle Testing in the Marine Environment". Materials Evaluation, April 1983.

- Carnevale, S.; "An Introduction to Atmospheric Diving Suits". Materials Evaluation, April 1983.

- Galerne, A. and Walker, D.; "Deep Water: The New Frontier for NDT". Materials Evaluation, April 1983.

- Anderson, C.C.; "A Review of Structural Inspection and Maintenance Experience at Ekofisk", Veritas Conference: Offshore Inservice Inspection and Monitoring, Oslo, 1979.

- An Assessment of Underwater NDT Equipment, Phase I (1981), Phase II (1982), DOE Project No. 538.

- Webborn, T. J.C., et al.; "Acoustic Emission Monitoring Techniques Applied to Offshore Structure - Subsea and Topside Applications". European Offshore Petroleum Conference, 1980, Paper No. 252.

- Tang, W.H.; "Probabilistic Updating of Flaw Information", ASTM, Journal of Testing and Evaluation, 1, 6, 1973.

- Loland, O. and Dodds, C.J.; "Experiences in Developing and Operating Integrity Monitoring Systems in the North Sea". Offshore Technology Conference, 1976, Paper No. 2551.

- Peterson, D.K., Bennett, S.D. and Kino, G.S.; "Real-Time NDE of Flaws Using a Digital Acoustic Imaging System". Materials Evaluation, 40, 11, 1982.

- Schmitz, V., Mueller, W. and Schaefer, G.; "A New Ultrasonic Imaging System". Materials Evaluation, 40, 1, 1982.
  Jan

- Segal, E., Notea, A. and Segal, Y.; "Dimensional Information Through Industrial Computerized Tomography". Materials Evaluation, 40, 12, 1982.

- Burstein, P., Mastronardi, R. and Kirchner, T.; "Computerized Tomography Inspection of Trident Rocket Motors: A Capability Demonstration".

- Dumousseau, P.F., Laffont, P. and Thebault, J.M.; "Experimental Study of Acoustic Emission Monitoring of Crack Propagation in Offshore Steel Tubular Joint". Offshore Technology Conference, 1979, Paper No. 3425.

- Murray, I.J. and Bewley, E.; "Structural Inspection from an Underwater Engineering Contractor's Viewpoint". European Petroleum Conference, London, 1982.

- The Welding Institute; "Size Measurements and Characterization of Weld Defects by Ultrasonic Testing, Part 2". Welding Institute Cambridge, 1982.

10. APPENDICES

APPENDIX A
COMPANIES SELECTED FOR THE ASSESSMENT

APPENDIX B
QUESTIONNAIRE GIVEN TO COMPANIES WITH NDE EXPERIENCE

APPENDIX C
NDE EQUIPMENT
DESCRIPTIONS AND SPECIFICATIONS

APPENDIX D
ON-GOING NDE RESEARCH PROJECTS IN THE UK

APPENDIX A

COMPANIES SELECTED FOR THE ASSESSMENT

1. COMPANIES AND INDIVIDUALS CONTACTED BY DIRECT INTERVIEW

All companies listed in this section were visited and asked to provide information regarding their experiences with NDE by filling in a questionnaire, a copy of which is provided as Appendix B. Companies actually responding to the questionnaire are indicated with an (*).

Company	Address	Person(s) contacted
CANADA		
* Ontario Hydro	800 Kipling Ave. Toronto, Ont. M8Z 5S4	J.A. Baron
* The NDE Service Group, Inc.	4109 Harvester Road Burlington, Ont. L7L 5J1	H. Cordes, General Manager
* John T. Hepburn Ltd.	914 Dupont St. Toronto, Ont. M6H 1Z2	G.J. Bailey, Manager - Q.A.
* Warnock Hersey Professional Services Ltd.	4 MacDonald Ave. Dartmouth, N.S. B3B 1C5	L.D. Knox, Vice President- Atlantic Region T.S. Milligan, Sr. Manager Radiography
* Oilfab Haltech Ltd.	19 Mosher Dr. Dartmouth, N.S. B3B 1E5	P.J. Hobbs, General Manager
* T.J. Inspection Services	P.O. Box 3088 Dartmouth East, N.S. B2W 4Y3	T. Monk J. Zohar

Company	Address	Person(s) contacted
* OIS Hanson	11 Morris Dr. Dartmouth, N.S. B3B 1M2	P.R. Dixon, General Manager
* Wolf Sub-Ocean Ltd.	55 Akerley Blvd. Dartmouth, N.S. B3B 1M3	R. Tyre, Operations Manager
* Weir Jones Eng. Consultants Ltd.	1574 West 2nd Ave. Vancouver, B.C. V6J 1H2	I. Weir Jones, President J.S. Reith A.S. Taylor, Manager, Special Projects R. Taylor
* Can-Dive Services Ltd.	1367 Crown St. North Vancouver, B.C. V7J 1G4	D. Romanuik, Operations Rep.
* Rig Inspection and Repair Services	863 Hamilton St. Vancouver, B.C. V6B 2R7	C.S. Roper
* Can Ocean Resources	610 Derwent Way New Westminister, B.C. V3M 5P8	M.L. Thornton, Q.A. Manager P. Gibb, Manager, R & D
* International Submarine Engineering Ltd.	2601 Murrey St. Port Moody, B.C. V3H 1X1	J. McFarlane, President M. MacDonald, Exec. Vice President
* Coast Testing	1474 Dominion St. North Vancouver, B.C. V7J 1B4	R.R.J. Kirby, NDT Tech. Supervisor J.M. MacDonald Senior NDT Tech.

Company	Address	Person(s) contacted
U.S.A.		
Krautkramer-Branson, Inc.	Mifflin County Ind. Park Lewistown, P.A.	T. Morrison, D. Lutz
Dunegan Corp.	30700 Rancho Viejo Rd. San Juan Capistrano, CA.	H. Dunegan
Reinhart & Associates, Inc.	5003 Hamilton Rd. Austin, TX.	E. Reinhart
Rockwell International	8900 Desoto Ave. Canoga Park, CA.	L. Maki F. Cubillos D. Dixon R. Alliston
Southwest Research Institute	6220 Culebra Rd. San Antonio, TX.	G.P. Singh A. Singh H. Hoffman A. Whiting J. Crane B. Jacobs
Spectron Development Laboratories, Inc.	3303 Harbour Blvd. Costa Mesa, CA.	B. Percy Hildebrand G. Fitzpatrick
Lehigh University, Institute of Fracture and Solid Mechanics, Packard Lab. Bldg. 19	Bethlehem, PA 18015	G.C. Sih D.Y. Tzou C.K. Chao

Company	Address	Person(s) contacted
EUROPE		
Det norske Veritas (Oslo)	Veritasveien 1 P.O. Box 300 1322 Hoevik, Norway	O. Foerli, Head of Section for Inspection and NDT
		P.S. Dalberg, Section for Inspection and NDT
		K. Hogmoen, Section for Inspection and NDT
		H. Solheim, Section for UW Inspection & Operation
		A. Skarsaeterhagen, Head of Section, Inspection Services
Det norske Veritas (Stavanger)	Musegate 1 P.O. Box 788 4001 Stavanger, Norway	R. Hansen, Section for NDT
		E. Nysted, Section for NDT
		G. Hansen, Section for NDT
		J. Sandved, Section for NDT
Det norske Veritas (Bergen)	Nygaardsgaten 114 P.O. Box 4252 5013 Nygaardstangen, Norway	G.I. Sletten, Underwater Tech.
		M. Rasmussen, Underwater Tech.
Phillips Petroleum Co.	P.O. Box 69 4001 Stavanger, Norway	H.S. Taylor, Principal Engineer
		J.L. Danielsen, Senior Engineer

Company	Address	Person(s) contacted
Fraunhofer - Institute for Zerstoerungsfreie Pruefverfahren	Universitaet Gebaeude 37 6660 Saarbruecken 11, West Germany	P. Hoeller, Director
		K. Goebbels, Head of Department
		H. Kapitza
		G. Dobmann, Head of Department
		H. Willems
Roentgen Technische Dienst bv	Delftweg 144 3046 NC Rotterdam, the Netherlands	J.A. deRaad, Development & Systems Manager
		R. vanAgthoven, Systems Development
Shell Research bv	Badhuisweg 3 1031 CM Amsterdam, the Netherlands	H. Bosselaar
Shell U.K. Exploration and Production Ltd.	1 Altens Farm Road Nigg, Aberdeen Scotland, AB9 2HY	J. Hendrix, Head of Engineering Dept.
		E.C. Faulds, Section Head, Structural Maintenance
		D.B. Keith, Head of UW & Structural Maintenance
		A. Dennis, Chief Inspector
Oceaneering International	Pitmedden Road Dyce, Aberdeen Scotland, AB2 0DP	M.D. John, Chairman
		G. Mills, Area ROV/Inspection Manager
		B. Reid, Project Engineer
		C. Priestly, Inspection Engineer

Company	Address	Person(s) contacted
BP Petroleum Development (U.K.) Ltd.	Farburn Industrial Estate Dyce, Aberdeen Scotland, AB2 0PB	S. Freeman, Head of Subsea Engineering
		G. Watson, Area Subsea Engineer-Operations
Oilfield Inspection Services (OIS) Ltd.	Silverburn Place, Bridge of Don Industrial Estate Aberdeen, Scotland, AB2 8BG	F. Rogers, Director & General Manager
Dept. of Energy, Petroleum Engineering Division	Thames House South Millbank, London, England, SWIP 4QJ	L.G. Ellis, Senior Structural Inspector
AERE Harwell	Oxfordshire, U.K. OX11 ORA	B. Hawker, NDT
		K. Newton, NDT
		C. Scruby, NDT
BIX Industrial Testing Ltd.	Dolphin House, Commerce Way Leighton Buzzard, Bedfordshire, England	M. Boyden, Director
		D.W. Powell, Group Sales Director
		M. Closier, Technical Director Imaging Division
The Welding Institute	Abington Hall Abington, Cambridge U.K. CB1 6AL	P. Mudge, Head, NDT Research Section
		A.B.G. Cameron, NDT Section
		J.G. Wylde, Principal Research Engineer
		H.G. Pisarski, Principal Research Engineer

2. ADDITIONAL CANADIAN AND FOREIGN COMPANIES WITH NDE EXPERIENCE

Companies marked with a (+) in this section were asked to provide information regarding their experiences with NDE by filling in a questionnaire, a copy of which is provided as Appendix B. Companies actually responding to the questionnaire are indicated with an (*).

	Company	Address
	CANADA	
+*	Eastern Technical Services	P.O. Box 13517, Station "A" St. John's, Newfoundland, A1B 4B8 and P.O. Box 1083 Saint John, N.B., E2L 4E6
+*	Bowe and Landry Ltd.	3420 St. Joseph Blvd. East Montreal, Quebec, H1X 1W6
+	N.D.E.O.A	P.O. Box 3022, Station "B" Saint John, N.B., E2M 4X7
+*	Research and Productivity Council (RPC)	P.O. Box 6000 Fredericton, N.B., E3B 5H1
+*	Stasuk Testing & Inspection Ltd.	7642 Winston Street Burnaby, B.C., V5A 2H4
+	Industrial Non-destructive Testing Ltd.	15 East 6th Avenue Vancouver, B.C., V5Y 1J3
+*	Trutom Ltd.	6077 Upper Lachine Road Montreal, Quebec, H4A 2C4
+	UCA Non-destructive Testing Ltd.	4001 - 9th Street N.E. Calgary, Alberta, T2P 6X8
+	Vindar Inspection Services Ltd.	37 Dufflaw Road Toronto, Ontario, M6A 2W2

Company	Address
CANADA CONT'D	
+* Babcock & Wilcox Canada	581 Coronation Blvd. Cambridge, Ontario, N1R 5V3
+* Techno Scientific Inc.	205 Champagne Drive Downsview, Ontario, M3J 2C6

Company	Address
U.S.A.	
+ Oceaneering International Inc.	10575 Katy Freeway Houston, Texas, 77024
+ Independent Testing Laboratories Inc.	P.O. Box 657, 1 Research Drive Searcy, Arkansas, 72143
+* Physical Acoustics Corp.	P.O. Box 3135, 743 Alexander Road Princeton, New Jersey, 08540
+ J.A. Jones Applied Research Co.	P.O. Box 217097 Charlotte, North Carolina, 28221
+* Acoustic Emission Technology Corp.	1812 J Tribute Road Sacramento, California, 95815
+* Battelle Pacific Northwest Laboratories	Battelle Blvd. Richland, Washington, 99352

	Company	Address
	EUROPE	
+	Unit Inspection Co. Ltd.	Sketty Hall, Sketty Park Road Swansea, West Glamorgan, U.K., SAZ 8QE
+	Unit Inspection of Ireland Ltd.	East Wall Road Dublin 3, Ireland
+	Metal and Pipeline Endurance Ltd.	Taylor Road Stotfold, Hitchen, Hertfordshire, U.K.
+	Solus Ocean Systems (UK) Ltd.	632 London Road Isleworth, Middlesex, U.K.
+*	Societe Generale de Surveillance (SGS)	1 Place des Alps, Casepostal 898 1211 Geneva, Switzerland
	Magnetische Pruefanlagen GmbH	Am Heilbrunnen 115, Postfach 76 7410 Reutlingen 1, West Germany
	The Danish Welding Institute	Park Allé 345, 2600 Glostrup, Denmark
+	Syminex	2 Bd de 1' Ocean (9e) 13275 Marseille Cedex 9, France
+*	British Gas Corp.	Engineering Research Station Killingworth, P.O. Box 1LH Newcastle upon Tyne, NE99 1LH
+	Cranfield Institute of Technology	Cranfield, Bedford, U.K. MK43 0AL

Company	Address
JAPAN	
+* Japan Inspection Co. Ltd.	15-8, Honjo Higashi 2-chome Oyodo-Ku, Osaka 531
Non-Destructive Inspection Co., Ltd.	2-32, Kyuhoji-cho Higashi-Ku, Osaka
SGS Far East Ltd.	Koujin Bldg., 1-2-3 Gokou-Dori Chuo-Ku, Kobe 651
Japan Machinery & Metal Inspection Institute	9-15, Akasaka 1-chome Minato-Ku, Tokyo
+* Chugoku X-Ray Co., Ltd.	4-10, Sanjo 2-chome Kure City, Hiroshima Pref. 737
Kansai X-Ray Co. Ltd.	7-21, Minami Kannon 2-chome Nishi-Ku, Hiroshima City 733

3. FOREIGN NDE AND DIVING COMPANIES

Companies listed in this section were contacted by telephone and asked to provide information regarding their experiences with NDE.

Company	Address	Person(s) contacted
Comex Houlder Diving Ltd.	Bucksburn House, Howes Road, Bucksburn, Aberdeen Scotland, AB2 9RQ	T. Aldridje Inspection Manager
Seaway Diving Stolt Nielsen	P.O. Box 9570, Egertorvet Oslo 1, Norway	T. Ek Operation Manager
Sub Sea Offshore Ltd.	Greenwell Base, Greenwell Road East Tullos, Aberdeen, Scotland	M. Gassaway
Thalassa Offshore (Scotland) Ltd.	Mains of Kirkhill Kirkhill Industrial Estate Dyce, Aberdeen, Scotland AB2 0ER	W. Becker
Wharton Williams Taylor	Farburn Industrial Estate Dyce, Aberdeen, Scotland	P.J. Elliot Manager, Inspection Dept.

4. NDE EQUIPMENT MANUFACTURERS

The following producers of NDE equipment were approached to provide technical information and data, including price, operational experience and test results on their NDE equipment.

- Krautkramer GmbH, Koeln, West Germany
- Karl Deutsch, Wuppertal, West Germany
- Teide GmbH & Risspruefanlagen, Essingen, West Germany
- Institute Dr. Forster GmbH and Co. KG, Reutlingen, West Germany
- Magnetische Prufanlagen, West Germany
- Heinrichs and Walther GmbH, Bocholt, West Germany
- Baugh and Weedon Ltd., Hereford, England
- Hocking Electronics Ltd., St. Albans, England
- Thorburns Technics (International) Ltd., Glasgow, Scotland
- Andrex Radiation Products, Copenhagen, Denmark
- Scanray A/S, Copenhagen, Denmark
- Tecups, Berlington, Mass., USA
- Panametrics, Waltham, MA., USA
- Osel - Offshore Systems Eng. Ltd., Great Yarmouth, England
- OIS - Oilfield Inspection Services, Great Yarmouth, England
- Mapel - Metal and Pipeline Endurance Limited, Hitchin, England
- Balteau Sonatest Ltd., Milton Keynes, England
- Inspectech Ltd., Scarborough, Ontario
- Trigen Instruments Ltd., Scarborough, Ontario

APPENDIX B

QUESTIONNAIRE GIVEN TO COMPANIES WITH NDE EXPERIENCE

1. Methods

Please state which of the following methods you have used:

1.1 Visual (Diver, RCV, Others).

1.2 MPI.

1.3 Ultrasonic (Manual Normal Probe Technique, Manual Angle Probe Technique, Automatic/Semi-Automatic Technique).

1.4 Potential Drop.

1.5 Cathodic Potential Measurements.

1.6 Radiographic Testing.

1.7 Eddy Current.

1.8 Leak Testing.

1.9 Acoustic Emission Testing.

1.10 Plastic Replica.

1.11 Thermography.

1.12 Acoustic Holography.

1.13 Tomography.

2. General Data

For each method identified in 1, please provide information on the following:

2.1 Operation (diver operated and assessed, diver operated with surface assessment, remote control with surface assessment).

2.2 Documentation (diver report, survey team report, hard copy video tape, magnetic disc, others).

2.3 Performance (on the basis of the minimum defect size detected or other specific criteria, rank the method as good, fair, unsatisfactory).

2.4 Price.

2.5 Availability in Canada.

3. Project Experience

Please identify the offshore NDE projects you have carried out and address the following:

3.1 Type of installation - floating structures, fixed structures, pipelines.

3.2 Constructional material.

3.3 Zone of inspection (spash zone, node, etc.).

3.4 Purpose of inspection (surface defects, internal defects, depth of surface defects, wall thickness measurements, etc.).

3.5 Equipment name and manufacturer.

3.6 Results of lab/site experiments.

3.7 Is the equipment available commercially?

3.8 Skill required from the operator.

3.9 The maximum water depth at which the equipment has been used.

3.10 Equipment performance (you may wish to mark them as good, fair or unsatisfactory).

4. Additional Comments/New Development

Please provide such additional comments that may either amplify your answers or assist our assessment. If you are involved in the development of novel techniques and equipment, please provide us with as much information as you can.

APPENDIX C

NDE EQUIPMENT DESCRIPTIONS AND SPECIFICATIONS

The principal components of NDE equipment currently used in offshore inspections are presented here.

The purpose of this appendix is to provide information on the hardware deployed for detection and measurement. It is beyond the scope of the study to compile an operational manual for the equipment.

Information source for this appendix has mainly been the literature supplied by the manufacturers.

C.1 Visual Inspection

Results of direct visual inspection are often recorded using photographs and/or video recordings. There are various systems currently available; two of these are the Nikonos underwater camera and the OSEL Hydroscan camera.

While the Nikonos is a sport diver's camera which can be used for weld photography, the Hydroscan camera (costing approximately CAD $8,500, converted from UK pound sterling) has been specifically designed for that purpose. Both cameras can be outfitted with stand-off prods to permit quick and accurate positioning over the surface to be photographed. To obtain the required photograph, the weld is cleaned and an appropriate magnetic particle inspection technique is used together with fluorescent ink. By using fluorescent inks, defects stand out vividly under ultraviolet light. However, as the amount of white (ambient) light increases, the contrast between defect and weld decreases, which only becomes a problem near the water surface.

Video is used by observers on the surface to check the work done by divers as well as for monitoring the general condition of structural parts. However, the video image normally lacks the resolution and quality that is required for detailed examination purposes. In the case of defects, it is therefore a common requirement to take colour photographs. This may be difficult when visibility in the water is very low. In such cases a low light intensity TV camera may be the best aid to a skilled diver. Stereo photographs provide additional information that aids interpretation of the findings.

C.2 Equipment Based on Electromagnetism

C.2.1 MPI

MPI systems manufactured for underwater application typically consist of three major components:

- a subsea unit;
- a surface control unit;
- an underwater U/V lamp.

The subsea unit has a pressure compensating housing, containing a transformer, power supply to the ultraviolet lamp, and a motor drive for the ink circulating system.

Connected to the subsea unit through a single umbilical cable, the surface control unit receives power from the transformer.

The underwater U/V lamp is also connected to the subsea unit through an umbilical which carries the constantly agitated magnetic ink fluid that is directed onto the area under examination by a nozzle through a control valve positioned in the lamp handle enabling single handed operation.

Underwater magnetisation can be safely achieved utilising either prod, coil conductor or electromagnetic yoke techniques described in Section 2.1.2.1.

Specifications for MPI systems manufactured by OIS and OSEL are included in Table C-1.

The equipment used with the Magfoil method, is the Flexiyoke EL60T manufactured by Henrichs & Walther GmbH, West Germany. The Flexiyoke EL60T features a fully flexible yoke magnet with easy adaptation to complex geometries. At a pole spacing of 170mm it gives a current density of 12 kA/m. The poles can be separated to more than 250mm, depending on geometry, and the flux density of 4 kA/m obtained will still be sufficient for reliable indications of the smallest flaws.

TABLE C-1
TECHNICAL SPECIFICATIONS FOR MPI EQUIPMENT
(Taken from manufacturers' brochures)

Dimensions	OSEL MPI	OIS Compact	OIS MkII
Surface Unit (mm x mm x mm)	362 x 527 x 305	350 x 250 x 255	480 x 250 x 250
Submersible Unit (mm x mm x mm)	647 x 317 x 457	310 x 240 x 285	Ø 260 x 450
UV Lamp	230 x 93 x 200 mm x mm x mm	Ø 120 x 210 mm x mm	Ø 120 x 210 mm x mm
Weights in Air			
Surface Unit	14 kg	26 kg	35.5 kg
Submersible Unit	78 kg	18 kg	56.8 kg
UV Lamp	2 kg	2.25 kg	3.5 kg
Weights in Water			
Submersible Unit	40 kg	9.5 kg	26 kg
UV Lamp	1 kg	0.5 kg	0.5 kg
Depth Rating			
Submersible Unit	305 m	No Limit*	No Limit*
UV Lamp	305 m	200 m	200 m
Electrical Supply	210/250 VAC, single phase, 36 Amp	110/120 or 220/240 VAC, single phase, 13 Amp	210/240 VAC, single phase, 30 Amp
Electromag. yoke	-	Articulated 12VDC	Articulated 5VAC or DC
Prods	1500 Amp AC or DC, variable output, open circuit at 8V	-	1500 Amp AC or DC, variable output, open circuit at 5V
Coil or Cable	55 ft. cont. loop, 1000 Amp AC or DC, 5V duty cycle	-	40 ft. cont. loop, 1000 Amp AC or DC, 5V duty cycle
Approximate Cost	CAD $35,400 (CAD price quote)	CAD $9,000 (converted from UK pound sterling)	CAD $16,500 (converted from UK pound sterling)

* due to oil filled pressure compensating housing.

C.2.2 Magnetography

Subsea components include two different yokes for various weld geometries, underwater power supply, tapes, fixing magnets, and auxiliary parts, Figure C-1a. The underwater power supply has an operational depth of 300m and lasts for an entire one-day operation before recharging is required. At present, the subsea equipment can be applied at nearly any position in dry zone, splash zone, or underwater to depths of 300 meters.

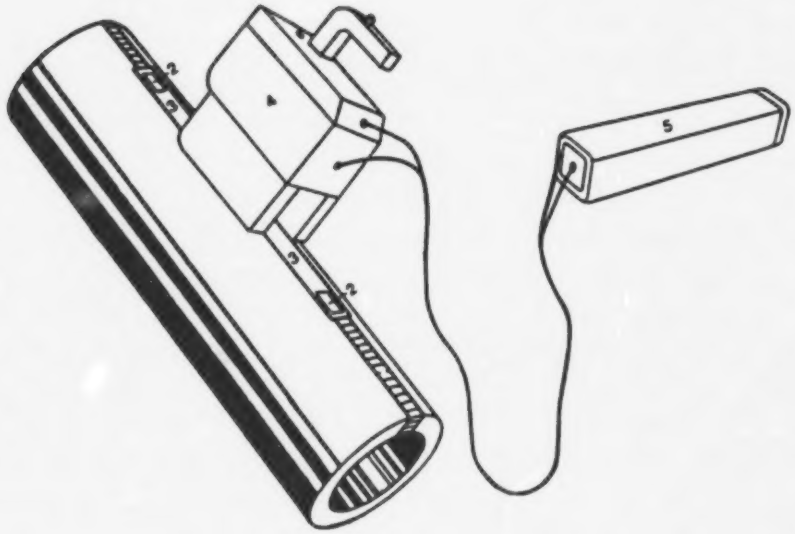
The above water evaluation system comprises three major components, Figure C-1b one of these is the power supply box with safety circuits, battery charger, and tape eraser tunnel. The second component is the tape scanner with calibrated tape tracking drum, amplifiers, and filters. The third unit gives scope representation and strip-chart recordings of the actual defect signals.

C.2.3 EMD

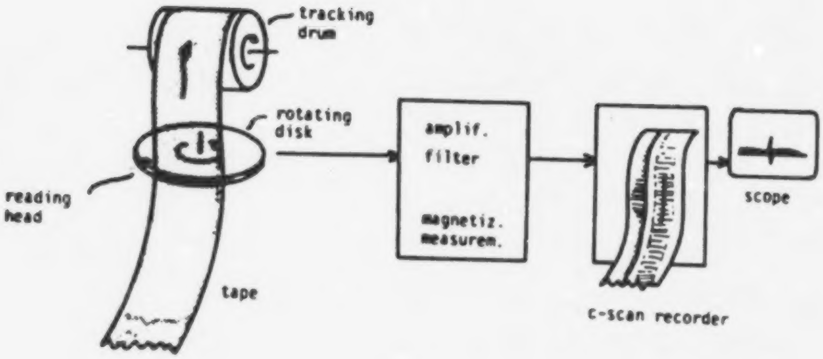
The EMD system manufactured by Thorburn Technics consists of an above water oscilloscope type unit and underwater probes connected to the unit by armoured cable of up to 350m. Equipment specifications are given in Table C-2.

C.3 ACPD Measurement

To provide for instantaneous calibration, and a direct display of crack depth, a microprocessor has been used in the ACPD unit developed by DnV. Once turned on, the processor will start to operate as soon as sufficient contact of the probe contacts has been obtained. The calculated crack depth is then indicated on a built-in LED display. In addition, the battery state is checked.



a) 1) Weld; 2) Permanent Magnet; 3) Tape; 4) Yoke; and 5) Power Supply.


tracking drum
rotating disk
reading head
tape
amplif.
filter
magnetiz. measurem.
c-scan recorder
scope

b) Magnetograph Tape, Scanning and Recording Scheme

Figure C-1 Magnetographic Equipment

(Taken from: Stumm, W.; "Magnetographic Weld Inspection System for Underwater Installations". Materials Evaluation, April 1983).

TABLE C-2
EMD EQUIPMENT
(Taken from manufacturer's brochures)

Specifications	Thorburn Technics EMD III Deep Sea
Dimensions (mm x mm x mm)	600 x 225 x 320
Weight in air:	18.0 kg
Power:	240 V or 120 V 48-440 Hz 90 W max.
Operating temperature:	0 degrees C to 40 degrees C
Cable:	Armoured; 150 m to 350 m lengths in 50 m increments
Probe bodies:	Straight or Right angle
Probe tips:	Intermediate, ø 7.5 mm
Pencil Point:	ø 1.73 mm
Approximate Cost:	CAD $26,500 (converted from UK pound sterling)

In order to maintain the exact potential contact spacing, a special probe has been designed. The depth of surface-breaking cracks in the weld or between the weld and base material of offshore tubular joints can be measured with this equipment. The whole system can be normally operated by one diver as the probe and the electronic container are attached to the structure by holding magnets while the crack area is magnetized with the prod method as used with MPI.

Another system, the OSEL Underwater Crack Microgauge, consists of a number of components including a subsea unit with battery pack, underwater probes, surface read-out unit, and umbilical cable for surface read-out. The subsea unit is fitted with powerful magnetic clamps so that it can be positively located on the structure being inspected, as are the two probes used to establish the A.C. field. Once the unit is fixed in position, the only operation required from the diver is manipulation of the measuring probe.

The subsea unit display, which is repeated on the surface read-out unit, consists of a digital read-out of potential plus 2 LED indicators. One LED shows when the A.C. field has been properly established, the other when good measuring probe contact has been achieved.

Power for the subsea unit is provided by a rechargeable battery pack which is replaceable underwater. The capacity of the fully charged battery pack is sufficient for 4 hours of continuous operation.

Technical specifications for the OSEL system are given in Table C-3.

C.4 Ultrasonic Testing

C.4.1 Probes

MatEval Ltd., U.K. is one designer and manufacturer of ultrasonic probes offering a comprehensive range of standard transducers. MatEval Ltd. also has the capability of designing probes for specific applications requiring immersion transducers, multi-element transducers and phased-array systems.

TABLE C-3
ACPD EQUIPMENT SPECIFICATIONS
(Taken from manufacturer's brochures)

Specifications	OSEL Underwater Crack Microgauge
Subsea unit dimensions (mmxmmxmm):	480 x 210 x 210
Surface unit dimensions (mmxmmxmm):	140 x 90 x 100
Operating depth:	305m
Weight in air:	18 kg
Weight in water:	9 kg
Measuring probe:	10 mm or 15 mm spacing
Field probe spacing:	200-300 mm either side of defect
Batteries (subsea unit)	12-1.5 V alkaline cells
AC field:	Approx. 2 Amps at 6 kHz
Measurement range:	0.1 mm min. on smooth surface 1.5 mm min. on rough surface
Accuracy:	10% of measured depth
Approximate Cost:	CAD $18,000.00 (converted from UK pound sterling)

In addition to MatEval Ltd., Harisonic Laboratories Inc., Connecticut, U.S.A., Panametrics Inc., Massachusetts, U.S.A. and Krautkramer Branson, Pennsylvania, U.S.A. are also major manufacturers of ultrasonic probes.

C.4.2 Thickness Measurement

Considering the application to underwater NDE, thickness measuring equipment can be categorized in two ways: units that have been designed specifically for the underwater application or compact above water units which can be encapsulated in watertight housings. (These watertight housings are manufactured by diving contractors or offshore NDE equipment suppliers). Two units falling into the former category are the WK-DMU designed by Wells-Krautkramer for Krautkramer Branson and the Baugh & Weedon SP200 Seaprobe.

Both the WK-DMU and the Seaprobe are hand held units activated by pressing the spring loaded transducer against the surface of the material to be measured.

Two units which may be encapsulated in underwater housings are the Nortec 123U and Panametrics model 5222UG. Using these devices, a probe connected to the unit by a cable is pressed against the surface to be measured.

For all units, the thickness readout is immediate and is presented to the diver on either a LCD or LED display. The diver then either records the information or relays the readings verbally to the surface.

Specifications for these units are included in Tables C-4 and C-5.

TABLE C-4

ULTRASONIC UNDERWATER THICKNESS GAGES

(Taken from manufacturers' brochures)

Specifications	Baugh & Weedon SP200 Seaprobe	Krautkramer Branson WK-DMU
Size (mmxmm)	ø 85 x 360	ø 80 x 310
Weight in air:	1.5 kg	1.5 kg
Thickness measuring range:	5.0mm-99.9mm in steel	4.0mm-99.9mm in steel
Accuracy:	±0.2mm	±0.1mm
Operational temperature:	-5 to 50 degrees C	-
Pressure tested depth:	200m	180m
Display:	3 digit LED	3 digit LED
Battery:	rechargeable 6V nickel-cadmium	rechargeable five 1.5V cells
Battery life:	2000 readings	8 hours continuous operation
Battery Charging time:	-	16 hours max.
Approx. Cost:	CAD $3,600 (Canadian Price)	CAD $6,200 (converted from US $)

TABLE C-5

ENCAPSULATED ULTRASONIC THICKNESS GAGES FOR UNDERWATER APPLICATION

(Taken from manufacturers' brochures)

Specifications	Panametrics 5222UG	Nortec 123U
Encapsulated Size (mmxmmxmm):	93 x 181 x 264	121 x 76 x 229
Weight in air:	8.1 kg	2.0 kg
Thickness	3.0mm-99.9mm in steel	1.3mm-254mm +
Resolution:	±0.01mm	±0.03mm max
Operational temperature:	0 to 50 degrees C	-
Pressure tested depth:	305m	105m +
Display:	4 digit LED	LCD
Battery:	rechargeable, 6V solid gel	rechargeable Nickel/Cadmium
Battery life:	8 hours continuous operation	10-12 hours continuous operation
Battery charging time:	16 hours max.	12-14 hours max.
Housing:	Welded aluminum	G.E. Lexan polycarbonate
Approx. Cost:	CAD $5,500 (converted from US $)	CAD $4,600 (Canadian price quote)

C.4.3 Flaw Detection and Sizing

Ultrasonic flaw detectors used underwater are above water units encapsulated in underwater housings. Several above water models are currently used for underwater NDE, including Baugh & Weedon's Ten Eleven S and Krautkramer Branson's USK7. Both units, once they've been encapsulated, are designed to be diver-held and self-powered; information is displayed on a CRT but no provisions have been made for recording the display. Interpretation of the display is consequently left to the diver. Specifications for both detectors are given in Table C-6.

A Subsea Ultrasonic Repeating System (SURS II) which permits interpretation by an NDE technician other than the diver is manufactured by Oilfield Inspection Services (OIS), Aberdeen in conjunction with Baugh & Weedon. SURS II is available in three combinations:

SURS II, System 1: Consists of a transmitter (Baugh & Weedon Ten Eleven S) encapsulated in a cast aluminum housing for underwater use, a surface receiver (Baugh & Weedon Ten Eleven S, not encapsulated) and the required umbilical between the units. Using this combination, the diver takes the measurements using the subsea unit; information is subsequently displayed on the diver's unit (transmitter) and is repeated on a surface unit (receiver) simultaneously. The diver therefore need not necessarily be a qualified NDE technician. Both units may be used independently for standard subsurface or surface ultrasonic testing. The operational depth for the subsea unit is 300m.
Cost: CAD $42,000, approx. (Canadian price quote).

SURS II, System 2: Is a single Ten Eleven S flaw detector encapsulated in the underwater housing for use subsea as a conventional flaw detector. This unit does not have transmit/receive capability.
Cost: CAD $19,000, approx. (Canadian price quote).

TABLE C-6

ENCAPSULATABLE ULTRASONIC FLAW DETECTORS FOR UNDERWATER APPLICATIONS

(Taken from manufacturers' brochures)

Specifications	Baugh & Weedon Ten Eleven S	Krautkramer Branson USK7
Encapsulated: Size (mmxmmxmm)	130 x 180 x 270	95 x 240 x 300 (without UW housing)
Weight in air:	5.6 kg	5.3 kg
Working temperature: (degrees C)	-15 to +50	-15 to +40
CRT display size:	70mm x 55mm	70mm x 55mm
Operating Frequency range:	0.5 MHz to 15 MHz	0.5 MHz to 10 MHz
Operating mode:	single, double, separate transmit.-and-receive	single or dual probe and thru-transmission
Test range:	10mm - 7m in steel	10m - 2.5m in steel
Battery:	rechargeable, NiCad	rechargeable, NiCad
Operating depth:	200m	-
Approx. Cost:	CAD $4,200 (Canadian price quote)	CAD $5,400* (Converted from US $)

* without housing.

SURS II, System 3: Has the same capability of System 1 with additional features. Both the transmitter and receiver are encapsulated for use subsea. Disconnection of the umbilical between units automatically converts both to conventional flaw detectors and they may therefore be used independently of each other when repetition of information on another unit is not required.
Cost: CAD $48,000, approx. (Canadian price quote).

For systems 1 and 3, up to 500m of umbilical may be used between flaw detectors.

Operated separately, the flaw detectors have a battery life of about 5 hours; used together, battery life reduces to approximately 4-1/2 hours.

C.4.4 Corroscan

Corroscan is equipment consisting of an automated scanner and above water control unit designed to monitor internal corrosion of pipelines, risers and other important equipment. The underwater scanner moves around the pipe on a chain, and ultrasonic signals as well as position signals for the transducer are transmitted through cables to a registration and processing system above water. Inspection results are available in real time, and all data are stored on magnetic tape for later analysis.

C.4.5 Ultrasonic Torch

The Ultrasonic Torch is a system which provides rapid screening of welds for the presence of cracks. It is capable of detecting all surface opening cracks above a predetermined size (eg. 20 mm long by 3 mm deep) and is capable of identifying their positions.

The Ultrasonic Torch system consists of three major components:

a) an underwater measuring device;
b) an underwater power supply and signal processing unit; and
c) a surface display console.

The measuring device (a pressure equalised measuring head mounted on the end of a short handle) sends signals to the power/signal processing unit which subsequently transmits the processed signals to a display console above water.

The measuring device (fitted with stand-off prods) is operated by a diver by placing the device on the surface of the member on which measurements will be made. The measuring head contains sensors which sense the proximity of the member under inspection and, by means of miniature closed loop servos, align a gimballed platform in a precise attitude relative to this member. Mounted on the gimballed platform is a specially designed ultrasonic transducer which scans the surface of the member and produces signals giving information about the position of the transducer relative to the inspected surface, and about defects in or near the welds.

While an A-scan display can be provided by the display console, the scanning transducer and signal processing equipment permit real-time mapping of the area under inspection. A permanent record of the inspection may then be obtained by photographing the display.

C.5 Radiographic Testing

A compact gamma radiographic unit jointly produced by OIS and CS Products is the Nautilus. The Nautilus is capable of holding up to 200 curies of Iridium 192 and has a depth rating of 750 m. The actual source is housed in a depleted uranium rotational chamber which is air-actuated from the surface to ensure safe working conditions, for those involved. The cost of the Nautilus unit is approximately CAD $12,000 (converted from UK pound sterling) but does not contain radioactive material as delivered by OIS.

Radiation monitoring is necessary when using Nautilus. This can be accomplished using a monitor such as the Graetz Gamma 100B from OIS which is encapsulated in an underwater housing. OIS is however developing a new model which will be available in 1984 at an approximate cost of CAD $1,500 (converted from UK pound sterling).

Additional equipment consists of a remote surface readout system giving a metered display which permits video recording of radiation levels.

C.6 Remotely Operated Vehicles and Atmospheric Submersibles

In the previous sections, NDE methods and equipment have been described which require the involvement of divers directly. This chapter deals with underwater operations where either the inspection is carried out by manned submersibles (where the operators are at atmospheric pressure) or by unmanned remotely operated vehicles (ROV's).

C.6.1 Manned Submersibles

Under this heading, further classifications are required owing to two different concepts: manned underwater vehicles and atmospheric diving suits.

C.6.1.1 Manned Vehicles

Manned vehicles are one of the next best ways of taking man and NDE equipment to the testing site. Some of these vehicles can hold several persons; one vehicle which can accomodate 5 persons to depths of 2000 ft. is the 17-ton Beaver. Two two-man vehicles are the Mermaid (operating at depths to 1000 ft.) and the 12-ton Pisces (rated to 8300 ft.). Mantis is a one-man vehicle which can dive rapidly to depths over 2000 ft. and perform tasks using strong manipulator arms.

C.6.1.2 Atmospheric Diving Suits (ADSs)

Atmospheric diving suits are a development of Oceaneering International and provide an alternative to deep water diving. Oceaneering has developed three models: the JET JIM, Wasp, and Wasp Inspector ADSs. The JET JIM features a 610 m depth capability, four 1.5 kW AC motors with variable pitch propellers, foot-operated thruster controls, 2-knot current bottom capability, and variable 0-60 lbs. buoyancy. Capabilities of the suit include video and still photography, anode replacement, NDT, cathodic protection measurement, 3-dimensional visual inspection and a variety of other repair, maintenance, and retrieval tasks. The size of the suit is 78" x 56" x 44" and weighs 780 lbs. in air thereby necessitating a vehicle launch/recovery system. Both the Wasp and Wasp Inspector have similar capabilities.

In the case of the Wasp, the deployment system consists of a cage or garage supporting the ADS that is lowered to the required working depth. Once this depth has been reached, the Wasp can be released and move about employing a lighter umbilical than would be possible without such a deployment cage.

C.6.2 Remotely Operated Vehicles (ROVs)

For visual inspection tasks and photographic work, ROVs frequently replace divers because of the unlimited amount of time they can remain underwater and the great depths to which they can dive. (One example, the Epaulard, is totally autonomous and can do photographic and bathymetric surveys down to 20,000 ft.). Generally ROVs are powered through umbilicals and can maneuver in small spots because of their small size.

Besides visual inspection, ROVs can carry out cathodic potential readings on structures and pipelines, and measure bury depths along buried pipeline routes. In the North Sea, upgraded ROVs are equipped with one or two black-and-white low light high-resolution TV cameras, a colour photographic camera, accurate depth sensor, heading sensor, pipetracker, cross trench profiler, and reference electrode for cathodic potential measurements. Results from surveys performed by these vehicles were found to have the same quality as those previously obtained from manned submersibles.

One such ROV is the Hydro-Products RCV-225. This vehicle can perform detailed underwater inspections to depths of 2,000 m. In addition to the vehicle itself, the RCV-225 system also consists of a deployment unit and a control van.

The deployment unit includes a protective ROV launcher with tether cable winch and a hydraulic power supply. The vehicle is transported to working depth in the launcher, performs the inspection task, and then returns for transport back to the deck. The vehicle can also be deployed from launchers attached to manned submersibles, diving bells, upper stacks, marine risers or guide wires.

The control van houses video tape recorders with monitors, a video control console and the vehicle control console. Depth, heading, lens pitch angle and other data are displayed on the television screen and recorded.

Performance characteristics, and size and weight data for the RCV-225 system are included in Tables C-7 and C-8.

TABLE C-7
RCV-225 SYSTEM SIZE AND WEIGHT
(Taken from manufacturer's brochures)

		Size			Weight	
Component	Location	Height	Width	Depth	Air	Water
Vehicle	U/W	51cm 20 in	66cm 26 in	51cm 20 in	82kg 180 lbs	-2kg -4 lbs
Control Station	Topside	80cm 31 in	56cm 22 in	78cm 30 in	158kg 350 lbs	-
Deployment Unit:						
Winch/skid/A-frame[1]	Topside	1.8m 6.0 ft	1.4m 4.5 ft	2.3m 7.5 ft	1980kg 4355 lbs	-
Hydraulic PS	Topside	0.8m 2.5 ft	0.6m 2.0 ft	0.9m 3.0 ft	200kg 440 lbs	-
Underwater launcher[2]	U/W	1.1m 3.7 ft	1.0m 3.2 ft	1.0m 3.2 ft	193kg 425 lbs	175kg 385 lbs

1. With 400m (1350 ft) armored cable.
2. With 120m (400 ft) tether cable.

TABLE C-8

RCV-225 VEHICLE PERFORMANCE

(Taken from manufacturer's brochures)

Orientation of Vehicle	Ability to Maintain Position Without High-Thrust Package	Ability to Maintain Position With High-Thrust Package
Into current (Forward)	1.25 knots	2.0 knots
Transverse	0.75 knots	1.1 knots
Reverse	1.2 knots	1.9 knots

Two systems similar to the RCV-225 are the Canadian built Dart and Trec systems from International Submarine Engineering.

Inspection of construction joints and high stress areas on concrete platforms often requires cleaning of marine growth from these areas. For this purpose larger ROV's have been fitted with hydrojects and telescopic suction pads (to keep the vehicle steady during the cleaning operation). These cleaning vehicles also possess one or two manipulator arms fitted with single jets to clean difficult areas. ROV systems that perform these cleaning tasks are the Snurre 1 and Snurre 2 by Myrens Verksted, Norway.

C.7 Prospective Inspection Equipment

C.7.1 Advanced Ultrasonic Testing

C.7.1.1 P-Scan

Based on P-Scan, DnV CORROSCAN for mapping corrosion of pipelines and risers was developed.

C.7.1.2 Rotoscan

Using Rotoscan, multiple crystal probes (at various angles) are placed in two housings on each side of the weld so that the whole depth of weld is being scanned including the wall thickness. The number of crystals depends on wall thickness. Usually a 5mm zone is scanned by one transducer. The scanner is positioned using a band. Rotoscan uses an ultrasonic micro- or mini-computer based system SONOLOG (developed by RTD) for data logging and A-scan, B-scan or C-scan image generation.

C.7.1.3 SUTARS

Technical specifications for SUTARS are given in Table C-9.

TABLE C-9

SUTARS TECHNICAL SPECIFICATIONS

Number of receiving sensors	2 to 6, as needed
Maximum area coverage (sector)	8" (203.2mm) x 25" (635mm)
Cell size	0.2" (5.08mm) x 0.2" (5.08mm)
Cell location accuracy	0.1" (2.54mm)
Maximum number of cells/sector	5000
Maximum sensor spacing	5" (127.0mm)
Minimum sensor spacing	2" (50.8mm)
Minimum pipe diameter for inspection	2" (50.8mm)
Maximum pipe diameter for inspection	48" (1220mm)
Thickness measurement range	0.05" (1.2mm) to 4.0" (101.6mm)
Thickness measurement accuracy	±0.003" (0.076mm)
Search unit size	0.125" (3.175mm) to 0.5" (12.7mm) round
Data acquisition rate	30/second
Data processing, printing rate	1200 baud (120 characters/second)
Data processing, recording rate	4800 baud (480 characters/second)
System power requirement	Less than 1000 watts
Total system weight	Less than 200 lbs. (90.72 kgs)
Maximum weight/module	Less than 40 lbs. (18.14 kgs)

C.7.1.4 Time-of-Flight System

The present time-of-flight system developed by Harwell costs approx. CAD $100,000 and includes the probe assembly, control and data acquisition electronics and software.

C.7.1.5 TREES

Turbine Rotor Examinational/Evaluation System (TREES) equipment specifications are given in Table C-10.

C.7.1.6 Phased Arrays

The phased array system developed at the Fraunhofer Institute has 24 individually controlled channels and consists of a transmitter/receiver unit, a delay unit, a microcomputer and image display and uses three different types of transducer arrays: annular arrays, linear arrays and planar arrays.

A similar linear array real-time imaging system has been developed at Stanford University (USA).

C.7.1.7 Ultrasonic Holography

Advanced electronic equipment containing a transmitting and a receiving unit, a mechanical scanner which moves either a plane or a focused probe in rectangular coordinates or a linear array and a powerful computer system was developed at Fraunhofer Institute. The computer system drives a graphic terminal to supervise and display the recorded data so that a parallel data-acquisition, -reconstruction and -visualization is possible. Highly advanced signal processing techniques are used (satellite-pulse -technique, pulse orientation, time-of-flight locus curves, etc.) to reconstruct the defects.

TABLE C-10

TREES TECHNICAL SPECIFICATIONS

Number of Focused Search Units	12
Number of Conventional Search Units	3
Operating Frequencies	5-10 MHz
Mechanical Scanner Repeatability:	
Circumferential	±0.1 degrees
Axial	±0.01" (0.25mm)
Mechanical Scanner Speed:	
Axial:	
Examination	0.3" (7.62mm)/min
Rapid Advance	0-3' (0.91m)/min
Rotational	15 rpm
Examinable Bore Length	0-30' (0.91m)
Examinable Bore Diameter Range	3-13" (76.2mm-330.2mm)
Power Requirements:	
Computer	230 VAC, 60 Hz, Single phase 30 amps
Data Acquisition/Mechanical Positioning	110-120 VAC, 60 Hz, Single Phase, 1 amp

The system includes:

- real time imaging;
- electronic scanning;
- variable focal length;
- automatic sweep focus;
- manual focus;
- magnification zoom;
- three-dimensional display;
- interchangeable scanning heads;
- arrays of multiple transducers;
- diver monitor.

C.7.2 Enhancement of Electromagnetic Methods

Since new methods and systems being investigated at the UK Welding Institute and at Harwell are still in the development stage, descriptions of equipment cannot be provided.

C.7.3 Computerized Tomography

Recently the medical tomography equipment has been modified or new equipment built to be used as an industrial NDE tool. Further details may be found in Segal, 1982 and Burstein; refer to General Bibliography.

C.7.4 Enhanced Visual Inspection

C.7.4.1 CARTIS

Using CARTIS, a system computer is linked to a real-time image processor that accepts signals from a variety of sensors including television cameras, CCD (charge coupled devices) arrays and x-ray image intensifiers. Once the signal has been translated into electronic signals, the CARTIS system uses its software to enhance, detect, or make decisions on the image seen.

Real-time radiography using high frequency electronic generators with computer control to provide the quality and stability of output desired.

C.7.4.2 Optical Holography

Design features of an underwater holographic camera are discussed in the literature[3.7].

APPENDIX D

ON-GOING NDE RESEARCH PROJECTS IN THE UK

1. Title:

Evaluation of defects in members of structural frameworks using resonant vibration techniques.

Institution:

Newcastle University, Newcastle.

Investigator(s):

Dr. D.M. Lilley, Dr. J.W. Bull/Civil Engineering.

Overall Aims and Applications:

The aim of this project is to develop a vibration test technique for members of a structural framework, to determine the presence of any cracks and, if present, their exact position and severity.

The results will be in the form of a report, computer program giving graphical results, in-situ vibration test equipment and method (possibility of remote control). It is hoped this will be significant in assessing the safety of in-situ offshore (and onshore) structural frameworks.

2. Title:

Specific electrochemical sensors for precise measurement of chemical species in seawater.

Institution:

Newcastle University, Newcastle.

Investigator(s):

Dr. J.V. Dobson/Physical Chemistry.

Overall Aims and Applications:

Marine subjects compatible with electrochemical sensors and techniques will be identified and researched.

Electrochemical sensors may be studied for gases or metal ions (including pH) with a view to developing useful instrumentation to furnish in situ type data on factors associated with structural integrity and corrosion of metal structures and ships or seabed studies.

3. Title:

Characterisation of acoustic emission signals for improved structural monitoring role.

Institution:

Cranfield Institute of Technology, Cranfield, Bedford.

Investigator(s):

Mr. B.S. Hockenhall, Dr. J. Billingham; School of Industrial Science.

Overall Aims and Applications:

The acoustic emission technique has great potential for both localised and global structural integrity monitoring of offshore installations. Current drawbacks to the technique include the difficulties and high cost of installing and monitoring a properly engineered grouping of transducers offshore and the problems of identifying "real" danger signals from the signal response from the overall structure. The objective of the current work is to improve the correlation of certain unique acoustic emission signals with particular degradation processes and incorporating simpler pattern recognition features into field equipment.

4. Title:

Structural integrity monitoring offshore with optical fibre devices.

Institution:

Cranfield Institute of Technology, Cranfield, Bedford.

Investigator(s):

Dr. J. Billingham, Mr. B.S. Hockenhull, Mr. T.E. Clifton; School of Industrial Science.

Overall Aims and Applications:

Suitably treated optical fibres can be used as strain monitoring devices. This project will continue to develop such devices as fatigue crack growth monitors and as crack detectors at critical locations on offshore structures. The work will include developing appropriate optical fibre crack growth monitoring devices for use offshore on steel and concrete structures. This will include laboratory studies and realistic trials in marine environments. Such information should enable safer opeation and/or more effective inspection/maintenance programs to be carried out. Important aspects of the work will be to develop suitably sensitive packages for detecting small crack openings for early warnings of crack formation, assessing the suitability of such devices for monitoring underwater fatigue crack growth in various likely configurations, develop both diver interrogated or surface interrogated devices and the best means of transmitting signals from subsea sites to the surface. This should result in the development of devices which could be used offshore to give warning of crack formation or to monitor crack growth situations.

5. Title:

The application of hydrogen permeation measurements to the monitoring of marine structures.

Institution:

North Western Universities Consortium, Manchester.

Investigator(s):

Dr. R.A. Cottis/Corrosion and Protection Centre, UMIST; Dr. R.A. King/Corrosion and Protection Centre Industrial Services (CAPCIS), UMIST.

Overall Aims and Applications:

Hydrogen-induced effects are one of the main factors restricting the selection of higher strength steels for offshore structures. The objective of this project is to develop a fundamental understanding of the factors influencing the permeation of hydrogen through a steel membrane, and to correlate the hydrogen permeation rate with mechanical damage caused by the hydrogen. A long-term objective of the proposed work is to provide a basis for the use of hydrogen permeation measurements as a monitoring technique for hydrogen damage, thereby providing a tool for the better control of cathodic protection systems and inhibitor additions to oil and gas pipelines. Results will be of use to all offshore suppliers, contractors and operators.

6. Title:

Magnetic crack detection of surface defects at welded joints by Hall effect devices.

Institution:

North Western Universities Consortium, Manchester.

Investigator(s):

Professor F.M. Burdekin/Civil & Structural Engineering, UMIST.

Overall Aims and Applications:

Present techniques of magnetic crack detection can be time-consuming at the fabrication stage and inconclusive when applied under water, particularly when access is difficult. This project aims to improve on present methods of magnetic crack detection, both at the fabrication stage and inservice, by the use of Hall effect devices to provide an electric signal output from sensors which can be displayed, recorded and subsequently analysed thus overcoming the above problems. In addition to improved detectability of cracks, such devices may also provide an indication of depth, not given by present techniques. The results will be made available to industry.

7. Title:

Squid magnetometers for non-destructive testing.

Institution:

University of Strathclyde, Glasgow.

Investigator(s):

Dr. G.B. Donaldson/Applied Physics; Dr. G. Hayward/Electronic & Electrical Engineering.

Overall Aims and Applications:

This is a speculative and innovative program, designed to study the usefulness of SQUID (superconducting quantum interference device) magnetometers as detectors of the magnetic anomalies produced by surface-breaking cracks in ferrous structures. Using a novel low-field magnetisation technique and gradiometric pick-up coils of a new design, we expect to be able to utilise the outstanding sensitivity of SQUIDs (up to five orders of magnitude better than, say, flux-gate magnetometers) to greatly improve on present crack detection techniques. For example, we should improve both minimum detectable crack volumes and maximum allowable transducer stand-off (say to 10cm). Moreover, we expect the technique to work for structures immersed in sea-water.

Beyond this program, the long-term aim of this project is to develop a portable underwater crack-scanning magnetometer system, requiring only a small low-power magnetisation energy supply, which would eliminate the need for the removal of marine growth and other deposits before testing.

8. Title:

Evaluation and development of non-destructive testing techniques.

Institution:

LONDON CENTRE, University College, London.

Investigator(s):

Dr. R. Collins/Mechanical Engineering; Professor D.H. Michael/Mathematics.

Overall Aims and Applications:

A.C. Potential Difference techniques for NDT of offshore steel structures:

(i) To develop non-contacting probes and probes of significant loop area capable of measuring through surface fouling.

(ii) To investigate preliminary observations that ACPD readings are affected by residual stresses. Work is required to exploit the techniques as a practical method for measuring residual stress.

9. Title:

Non-destructive evaluation of marine structures, using ultrasonic techniques.

Institution:

LONDON CENTRE, University College, London.

Investigator(s):

Dr. L.J. Bond/Electronic & Electrical Engineering.

Overall Aims and Applications:

To improve existing ultrasonic inspection techniques and then to provide the theoretical understanding of wave propagation and scattering required for the development of new and quantitative techniques which will provide full defect characterisation and residual stress measurement, as required for fracture mechanics on steel structures. Computer models will be produced having application in understanding and overcoming a wide range of real NDT problems.

10. Title:

Electromagnetic detection of surface defects in marine installations.

Institution:

Brunel University, London.

Investigator(s):

Dr. J. Blitz/Physics.

Overall Aims and Applications:

Use of multi-frequency eddy currents to detect and examine surface defects in metal structures forming part of marine installations, and to resolve effects of changes in magnetic permeability, electrical conductivity, and lift-off, e.g. as occurring with welds. This should result in improvements in assessing the integrities of marine structures and should prove to be of particular value to organisations concerned with North Sea exploitation.

11. Title:

Nondestructive inspection of offshore structures by computerised scanning with gamma-photon counters.

Institution:

Brunel University, London.

Investigator(s):

Mr. B. Bridge/Physics.

Overall Aims and Applications:

Construction of prototype device for underwater NDT using ionising radiation but without film, built round 36" riser as test piece. Images computer reconstructed by scanning both through-transmitted and Compton backscattered radiation with array of high collection-efficiency gamma-photon counters. Relative merits of the two methods compared in the presence of simulated defects and marine growth. Performances compared with theoretical equations already developed by the investigator. The potential of the fibre optic links between scintillators and electronics evaluated. Potential attractions of the method: (i) doesn't require complete removal of marine growth; (ii) wide range of inspection speed versus minimum detectible size options, impossible with film (e.g. large defects detectible at rapid scanning speeds, small defects detectible by sacrificing speed); (iii) no underwater electronics (apart from electric motor) if fibre optic linkages are successful.

12. Title:

Ultrasonic arrays for flaw location and characterisation.

Institution:

University of Strathclyde, Glasgow.

Investigator(s):

Professor T.S. Durrani, Dr. G. Hayward, Dr. A. McNab/Electronic & Electrical Engineering.

Overall Aims and Applications:

Studies on 1-D arrays at Strathclyde have established their unique ability in locating structural defects without the need for mechanical scanning. The project is aimed at extending present work to the evaluation of these arrays for defect sizing and characterisation over a larger region of interest. The endpoint of the research effort would be the development of prototype hardware, involving state-of-the art instrumentation for accurate defect location and identification. When incorporated as a stand-alone inspection tool or part of an automated module, the system is aimed at producing more accurate and reliable inspection results with a minimum of operator dependence. As such, it will be widely acceptable to all offshore operators involved in inspection and maintenance.

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

ASSESSMENT OF NON-DESTRUCTIVE TECHNOLOGY REQUIRED FOR INSPECTING OFFSHORE STRUCTURES

EDITED BY
D.K. MAK

OCTOBER 1984

ENERGY RESEARCH PROGRAM

153p.

PHYSICAL METALLURGY RESEARCH LABORATORIES
REPORT: ERP/PMRL 84-56(TR)

MICROMEDIA

88-04575/

PHYSICAL METALLURGY RESEARCH LABORATORIES
REPORT ERP/PMRL 84-56(TR)

ASSESSMENT OF NON-DESTRUCTIVE TECHNOLOGY REQUIRED FOR INSPECTING OFFSHORE STRUCTURES

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D.K. Mak

PREFACE

This report represents the technical content of a survey on NDT technology available, or being developed for, the inspection of offshore structures. The work was performed by M. Tomin, O. Rengaard and S. Dubec of Det norske Veritas (Canada) Ltd. under DSS contract no. OSQ83-00035 on behalf of PMRL/CANMET, and represents, in the editor's judgement, a useful and critical review of the state-of-the-art of NDT technology.

The findings and opinions in the report do not necessarily reflect the views of the editor or his colleagues at CANMET.

LABORATOIRES DE RECHERCHE EN MÉTALLURGIE PHYSIQUE
RAPPORT PRE/LRMP 84-56(TR)

ÉVALUATION DES TECHNIQUES PAR ESSAIS NON DESTRUCTIFS REQUISES POUR L'INSPECTION DES STRUCTURES AU LARGE DES CÔTES

Édité par

D.K. Mak

PRÉFACE

Le présent rapport comprend le contenu technique d'un sondage sur les techniques par essais non destructifs (END) disponibles ou en voie de développement requises pour l'inspection des structures en mer. Ce travail a été effectué par M. Tomin, O. Rengaard et S. Dubec de la Det norske Veritas (Canada) Ltd. en vertu d'un contrat MAS nº OSQ83-00035 pour le compte de LRMP/CANMET et constitue selon l'éditeur une révision cruciale et utile des techniques modernes par essais non destructifs.

Les opinions et conclusions exprimées dans ce rapport n'engagent en rien la responsabilité de l'éditeur ou celle de ses confrères de CANMET.

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1. INTRODUCTION

1.1 Objectives and Scope

The study reported herein was commissioned by the Canada Centre for Mineral and Energy Technology (CANMET) to:

- evaluate the current state-of-the-art in non-destructive evaluation (NDE) techniques for the inspection of offshore structures and to
- propose recommendations for future development work on the most promising NDE methods and equipment.

Both the currently used and prospective NDE techniques have been reviewed. The currently deployed NDE methods used in offshore inspection that are addressed in the report are:

- visual inspection by divers and remotely operated vehicles (ROV);
- methods based on electromagnetism such as magnetic inspection, magnetography and the eddy current technique;
- AC potential drop measurement;
- ultrasonic testing;
- radiographic testing.

The following prospective NDE methods have also been assessed:

- acoustical holography;
- ultrasonic tomography.

The principal components of equipment for each method have also been described and their specifications given.

The assessment of inspection methods used for the NDE of offshore structures was based on such criteria as cost-effectiveness, quality, reliability and applicability as to water depth.

1.2 Methodology

Detailed information on various NDE techniques and equipment that are currently available or are being developed where obtained by surveying leading companies and research organizations in Europe, North America and Japan.

In addition, VERITAS' longstanding involvement in the survey of offshore structures has resulted in the establishment of a unique data bank, enlightened by the experience accumulated over many years. The study has benefitted considerably from this.

The information collected was critiqued and assessed on the basis of criteria developed in the light of experience gained from the inspection of structures in various offshore locations.

1.3 Non-destructive Evaluation of Offshore Structures - An Overview

"Non-destructive evaluation" of an offshore structure, or components thereof, is defined here as the process whereby the locations and characteristics of material flaws in the structure can be determined without impairing the functional capability of the structure or its components.

NDE is used for inspection during fabrication and when the structure is in service. This study pertains mainly to the in-service inspection of offshore structures.

The objective of in-service inspection is to ensure that the structure remains safe during its lifetime and that any defect or damage is detected in time for appropriate remedial measures to be taken to preserve the integrity of the structure.

Offshore inspection differs from inspection of other types of installations in respect of the following:

- limited accessibility (sea storms, aqueous environment, marine growth, etc.);
- hazardous areas;
- new and untested designs;
- large structures;
- consequences of failure (e.g. riser rupture within the concrete shaft);
- high costs (production loss, inspection by divers, ROV's, etc.);
- deterioration processes dependent on environment;
- limited space on board of installations.

The most problematic aspects of the NDE of offshore structures arise from the need to carry out inspection underwater.

Underwater inspection has been categorized into the following types:

Type I	General visual inspection (no cleaning) referred to as the green survey.
Type II	Close visual inspection (cleaning generally required) referred to as the blue survey.
Type III	Inspection using the non-destructive testing, referred to as the red survey.

When using NDE techniques for the Type III inspection, the principal concern is finding crack-like (planar) defects. The cracks may have developed as fatigue cracks, corrosion fatigue cracks, stress corrosion cracks, hydrogen induced cracks, lamellar tear cracks, etc. In most cases these cracks develop in areas of high stress concentrations from initial fabrication defects induced, especially in welds, during fabrication, transport and assembly of the structure.

The in-service inspection of offshore structures does not duplicate the NDE inspection at the fabrication stage. The goal of underwater NDE inspection is not therefore to look for common defects in welded joints such as porosity, lack of fusion, lack of penetration, undercuts, underfills, etc.; rather, it is to detect surface breaking cracks which may have been identified during Type I and Type II inspection. For example, according to the UK guidelines for inservice inspection, 10% of all welds should be inspected for cracks every five years. Using probabilistic analysis it was found[1.1*] that an evaluation of a 10% random sample of all welds results in the same probability of finding a crack as if evaluating 10% sample taken from the fifty highest stressed welds. It is of importance therefore, to properly identify the "critical zones" on the structure when planning an inspection program.

Current rules, regulations and guidelines mainly cover inservice inspection of the primary and secondary structure of offshore installations[1.2-1.6]. Fig. 1.1 shows a comparison between British, Dutch and Norwegian requirements to underwater inspection of steel structures. Rotational inspection tends to be the technique currently used for most offshore structures.

Offshore regulations require periodic inspection annually, biannially and 5-yearly, the latter to be spread out as annual/biennial inspection. In addition, special inspection is required in connection with damage or suspected damage and repair. Norwegian Petroleum Directorate (NPD) may also require two additional inspections, namely "initial inspection" after installation and "start-up inspection". The latter is in particular used for pipeline/riser start-up.

---

[*] Numerical superscripts identify references listed in Chapter 8.

FIGURE 1.1

STEEL STRUCTURES UNDERWATER INSPECTION

	GB			NL			N
							NPD
	ANNUAL	BIANNUAL	5-YEARLY	ANNUAL	BIENNIAL	5-YEARLY	ROTATIONAL
MECHANICAL DAMAGE		X	X	X			X
GENERAL CORROSION/PITTINGS		X	X	X			X
MARINE GROWTH		X	X	X			X
SCOUR, DEBRIS		X	X	X			X
INSPECTION OF ANODES		X	X	X			X
POTENSIAL READINGS			X		X		X
CLOSE VISUAL INSPECTION			X			X	X
INSPECTION OF REPAIRS	X		X	X			X
NON-DESTRUCTIVE TESTING			X		X	X	X
THICKNESS MEASUREMENTS			X		X	X	X

A 4-5 year program is set up for the assessment of long-term integrity. This program is then generally spread over the whole operation period and thus becomes a part of the periodic annual/biennially program;it consists of two parts, a mandatory inspection for short term safety and a long term inspection.

For each installation the annual program is normally specified in inspection guidelines. In addition to a general part, they usually contain the following:

- type of inspection;
- extent of inspection;
- procedures;
- equipment;
- personnel.

There is clearly scope for the improvement of the presently available NDE techniques. The reliability of NDE methods are affected by such factors as environmental constraints, limited experience and training of the diving inspectors, stress and fatigue of the divers, inadequate equipment and procedures. The problems encountered range from the non-detection of a significant defect to the detection of a defect where none exists.

Available information on inspection reliabilities, which may be expressed in terms of the probability of detection and correct characterization is scarce and often qualitative in nature. This limits the ability to optimize inspection efforts at the present time. More work should be done in establishing reliability data for the NDE methods currently in use, or under development, for underwater inspection.

Generally cost-effective operations of offshore installations should incorporate a proper coordination of design and inspection planning. The total costs of design, production, operation, and inspection should be minimized taking into account the following factors related to inspection:

- determination of design-critical defect size;
- design for inspectability;

- planning of inspection;
- inspection operations;
- evaluation of results;
- acceptance criteria reflecting expected reliability.

It is hoped that the assessment contained in this report constitutes a contribution to defining the reliability of the available NDE techniques as well as identifying where future research and development in this field will be most beneficial.

2. CURRENT NDE TECHNIQUES FOR OFFSHORE INSPECTION

2.1 Inspection Methods

Methods currently used for underwater inspection include the following:

- visual inspection;
- methods based on electromagnetism;
- potential drop measurement;
- ultrasonic testing;
- radiography.

2.1.1 Visual Inspection

Visual examination is fundamental to virtually all in-service NDE performed on offshore structures. Visual inspection programs are structured to examine the general condition of the structure with the purpose of detecting obvious damage (type I survey), and then more closely examine areas of high stress concentration ("hot-spots") or previous damage (type II survey). The type II survey also requires the diver/inspector to check underwater structures for coating and corrosion damage, anode condition, marine growth, scouring and debris.

Depending upon the results of the type I and II visual examinations, detailed, instrument-assisted, type III examinations (described in subsequent sections) may be required. Regulatory requirements and the operators' program also require that certain node joints, key welds and other "hot spots" be given a type III survey on a periodic basis; type III surveys are considered to be beyond the realm of visual inspection alone.

In most situations visual examination is affected by water clarity and illumination. In addition, physiological and psychological problems which increase with depth limit the efficiency and ultimate capability of divers. Hence, the use of remotely operated vehicles (ROVs), manned submersibles and atmospheric diving suits is rapidly evolving for visual examination, repair and maintenance work.

Reporting is the most important part of visual examination. When using an improperly qualified diving inspector, irrelevant findings are often reported while significant defects may be left unreported. Application of other (instrumented) NDE techniques depends to a large extent on results of the visual inspection.

2.1.2 Methods Based on Electromagnetism

Surface breaking defects in ferromagnetic materials cause local changes in magnetic permeability hence, when a magnetic field is induced in the material, magnetic flux leakages will occur at the defects. The flux leakages can be detected in a number of ways thereby delineating the defects. Three methods based on electromagnetic principles are often used for underwater applications:

- magnetic particle inspection (MPI);
- magnetography;
- eddy current method.

2.1.2.1 Magnetic Particle Inspection (MPI)

Magnetic particle inspection is the most commonly used technique for detailed examination of offshore structures for stress cracks. Its purpose is to enhance the appearance of cracks for ease of visual detection, thus providing a means for type III visual examinations. In principle, MPI performed underwater does not differ from above water wet magnetic particle testing which is described in detail in BS6072 (Method for Magnetic particle flaw detection), ASTM SE-138 (Standard Method for Wet Magnetic Particle Inspection), and other literature[2.1, 2.2].

2.1.2.1.1 Principle of MPI

The basic technique for MPI consists of evenly flooding the area of concern with a brightly coloured or fluorescent ink containing tiny magnetic particles. By temporarily magnetizing the area under examination, the magnetic particles will migrate to any surface-breaking cracks in that area. With the aid of bright or ultraviolet (in the case of fluorescent inks) light, the diver is then able to discern the cracks (Fig. 2.1).

Two major factors influence the effectiveness of MPI:

- orientation between the magnetic field and the defect;
- strength of the magnetic field.

2.1.2.1.2 Magnetization Methods

Ferromagnetic materials can be magnetized in two ways:

1. Direct magnetization. A magnetic field is induced in the material by an electric current passing through it using magnetization prods, Fig. 2.2. AC current of 2.5-4.0 A/mm r.m.s. will generate the necessary tangential peak field strength. The tips of the prods are fitted with special material (either a special lead or other low melting alloy) to avoid local heating and burn marks at the test surface.

   Recommended prod spacing is from 150-300mm while prod operation should be 20-30 degrees from the direction of the weld bead. Spacing between successive tests should be 40-50mm (Fig. 2.3).

2. Indirect magnetization. Magnetism is induced by placing the material in a strong magnetic field which can be generated by:

   - a magnetization coil which should be placed 50-100 mm outside the test area. Surface cracks parallel to the coil will be detectable;

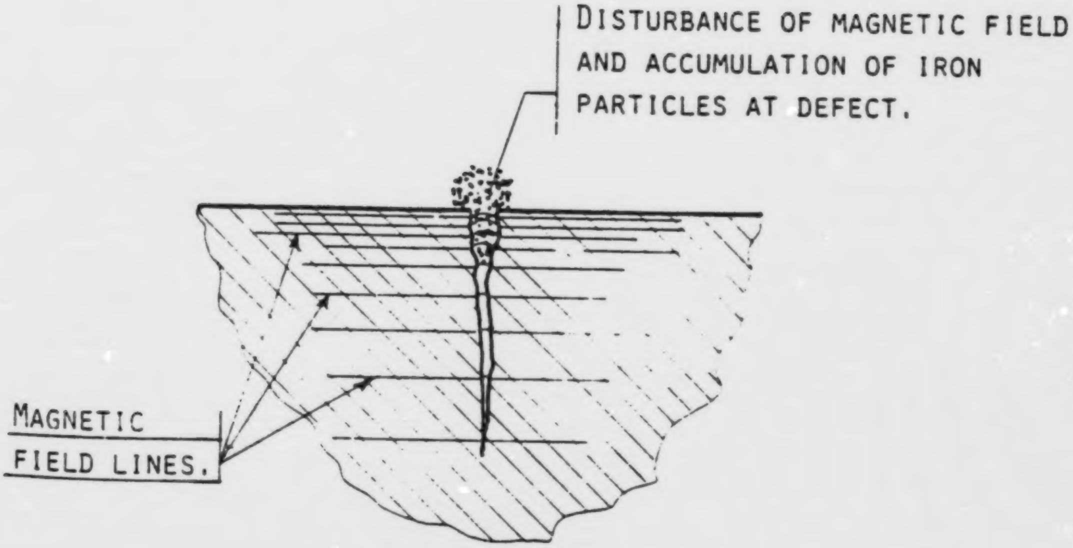

DISTURBANCE OF MAGNETIC FIELD
AND ACCUMULATION OF IRON
PARTICLES AT DEFECT.
MAGNETIC
FIELD LINES.

Figure 2.1 Delineation of Defects by Magnetic Particles 2.3

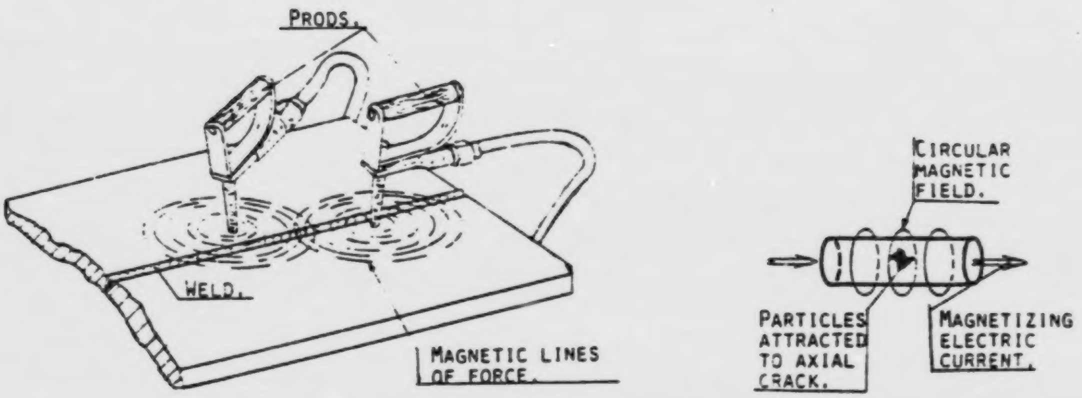
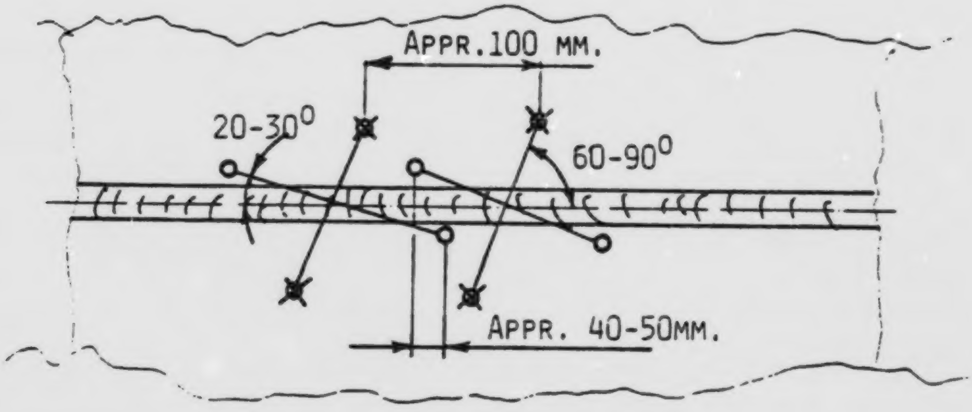

PRODS.
WELD.
MAGNETIC LINES OF FORCE.
CIRCULAR MAGNETIC FIELD.
PARTICLES ATTRACTED TO AXIAL CRACK.
MAGNETIZING ELECTRIC CURRENT.

Figure 2.2 Direct Magnetization 2.3


APPR.100 MM.
20-30^0
60-90^0
APPR. 40-50MM.

☒- Yokes
○- Prods

Figure 2.3 Optimal Prod or Yoke Positions 2.3

- a parallel conductor. Cracks running parallel to the conducter in the area between the loop can be detected;
- an AC electromagnetic yoke which generates a longitudinal magnetic field, Fig. 2.4;
- a permanent magnet yoke which is similar to the AC electromagnetic yoke except that the field strength is not adjustable and may be of limited strength.

Yokes should be oriented at an angle of 60-90 degrees from the direction of the weld as shown in Fig. 2.3.

2.1.2.1.3 Magnetic Field Strength

If the magnetic field is too weak, the magnitude of flux leakage at discontinuities will be insufficient for magnetic particle migration. Similarly, if the field is too strong (approaching magnetic saturation) differences between the overall field strength and flux leakage locations will be insufficient to cause particle movement. In either case detectability will be adversely effected.

Magnetic field strength should be verified with a Hall probe or similar instrument. This especially applies to complex surface geometries such as node welds. Field strength may be verified above water by using models with the same geometries and materials as the objects to be examined.

All electromagnetization should be done with alternating or half wave rectified current which should be measured as an r.m.s. value.

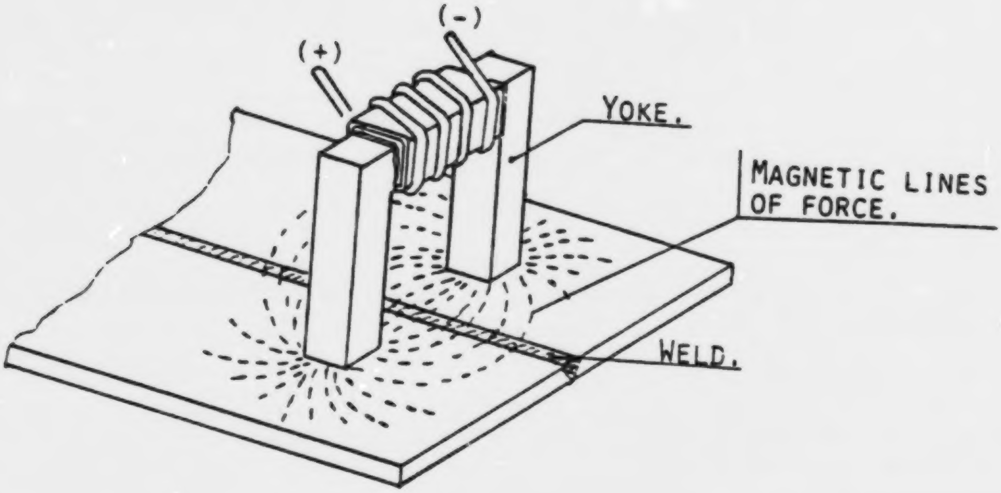
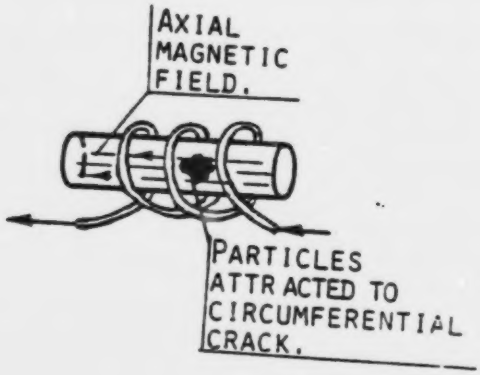

(+)
(-)
YOKE.
MAGNETIC LINES OF FORCE.
WELD.

Figure 2.4 Indirect Magnetization [2.3]


AXIAL MAGNETIC FIELD.
PARTICLES ATTRACTED TO CIRCUMFERENTIAL CRACK.

2.1.2.1.4 Documentation of MPI Results

When using fluorescent or non-fluorescent magnetic particles, still photography or video should be used to document examination results and actual magnetization setup. However another technique, the Magfoil Method, has been developed and provides immediate documentation of test results[2.4]. Magfoils contain magnetizable particles which are held with other substances in a flat, hose-type container made of flexible foil. In addition, a mixture of fluids is contained in another partition of the Magfoil. To use the Magfoil, the operator applies pressure to the partition containing the fluids. After the partition breaks, the particles and fluids are mixed, the Magfoil is pressed to the surface over the defect area and is then magnetized for up to 2 minutes. Once the magnetic particles have accumulated over the flaw and the fluids have hardened these particles into position, the Magfoil can be removed for evaluation purposes.

2.1.2.2 Magnetography

Magnetography was developed and patented by Magnetische Pruefanlagen GmbH, Reutlingen, West Germany under the commercial name Magneto Marine Method.

The physical principle of the magnetographic method is similar to MPI in that it also utilizes flux leakage as a means of identifying discontinuities. Magnetography does not use accumulation of magnetic particles for defect delineation, rather the disturbed magnetic field is directly stored on a flexible magnetic tape which is stretched over the weld area to be inspected[2.5]. In typical underwater applications, a weld length of about 0.5m is inspected in one procedure. A short magnetizing pulse of about 15ms duration, fed from a battery-supplied capacitor into a yoke, magnetizes the weld area over the yoke length and records the stray flux caused by the surface breaking cracks onto the tape. The tape is then taken to the surface where it is processed, the signals displayed on an oscilloscope or reproduced on a strip chart (C-scan record) and the results interpreted by a qualified technician.

2.1.2.3 Eddy Current Method

Eddy current testing is an NDE method based on the principle of electromagnetic induction and was originally developed for continuous testing of tubular products. The test is performed by passing the tube through or near a coil energized with alternating current. The presence of the tube modifies the impedance of the coil which varies according to several paramters: the distance between the coil and the tube, dimensions of the tube, electrical conductivity, and magnetic permeability of the tube. The impedance changes caused by localized differences (material defects) in the tube then produce electrical signals which are amplified and modified to give the required defect indication (mechanical, digital, etc.).

Applying this principle for underwater applications, Thorburn Technics International (TTI) Ltd., Glasgow, Scotland, recently developed the Electro-Magnetic Detection (EMD) technique. Using EMD, signals are processed using a balanced AC bridge detector system, making it possible to examine undressed (rough) welds.

2.1.3 AC Potential Drop (ACPD) Measurement

The AC potential drop technique developed as a tool for measuring the depth of surface-breaking cracks identified visually through MPI. Although the principle of the method was well known[2.6], DnV further developed this technique with the necessary instrumentation for underwater use.

2.1.3.1 Principle of ACPD

The method is based on the principle that a skin effect limits A.C. current to a very thin surface layer in metals. When a surface breaking crack is encountered the current is forced down into the material and around the crack ends (Fig. 2.5). Thus, when electrical field density is measured between two contacts placed on the surface of a test piece, the measured potential across a crack will increase with crack depth because the surface current path and hence effective resistance increases.

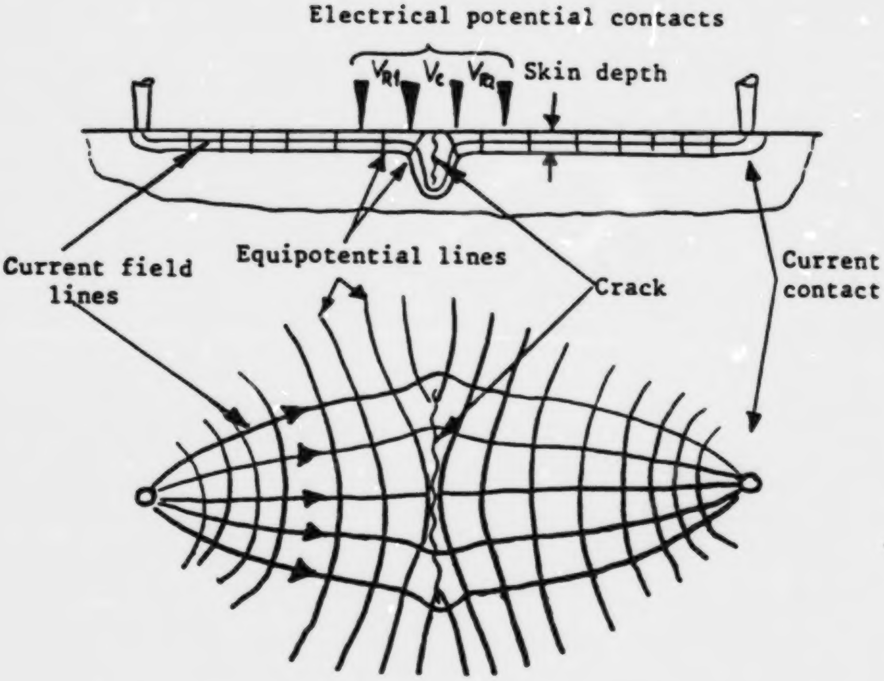

Electrical potential contacts
V_{R1}
V_c
V_{R2}
Skin depth
Current field lines
Equipotential lines
Crack
Current contact

Figure 2.5 A C Field Distribution Around a Surface Breaking Crack 2.7

2.1.4 Ultrasonic Testing (UT)

2.1.4.1 Principle of UT

When testing materials with ultrasonic waves, high-frequency sound waves propagate in solid bodies as directed beams, with very little attenuation. If the material is homogeneous the velocity of the propagating waves is constant. Hence, by measuring the time it takes for the wave to travel through the material, its thickness can be determined. In addition, at interfaces between media with different acoustic properties, such as air and metal, the waves are almost completely reflected. This makes it possible to detect cracks, inclusions and other flaws by means of ultrasonic waves.

To generate sound waves, an electric pulse is generated in the test instrument and transmitted to a transducer (transmitter) which converts the electric pulse into mechanical vibrations. These vibrations are transmitted into the object being tested where they are scattered, attenuated, reflected and resonated. A portion of this energy returns to the transducer (receiver) where it is reconverted to the electrical energy and transmitted to the test instrument where it is amplified and displayed, either digitally or on a cathode ray tube (A-scan).

For the testing of materials, piezo-electric crystals (commonly quartz or barium titanate) formed as thin plates are used for generating ultrasonic waves. If an alternating voltage is applied to the electrodes, the plate will vibrate with the frequency of this voltage, i.e. the transducer emits sound waves. Conversely, a sound wave striking the transducer produces a voltage at its electrodes.

2.1.4.2 Basic UT Methods

Ultrasonic testing of materials may be performed using the following basic methods:

- the reflection (pulse-echo) method;
- the transmission method;
- the immersion method.

Reflection (pulse-echo) Method

When an ultrasonic pulse is transmitted to the object, the time delay between the initial pulse and the echo from the back surface, or from a flaw inside the object, is measured (Fig. 2.6). Using this method, the thickness of the material and location of any flaws can be located exactly from one side of the object.

Transmission Method

Using the transmission method (Fig. 2.7), a pulse generated on one side of the test piece is received on the other side. (Access to both sides of the specimen is therefore required). The time-delay between signal transmission and reception is then measured. Defects are subsequently detected because of a decrease in signal strength, appearing as a reduction in echo height.

Immersion Method

One disadvantage of applying the transducer directly to the surface of the test piece is that the transmitted pulse tends to mask out those echos which arrive during or immediately after the transmission phase. Hence, information about near surface discontinuities is lost in the "near-field dead-zone". The immersion method (Fig. 2.8) has the advantage that the near-field dead-zone will occur in the water. Therefore defects located closer to the surface of the object can be detected more easily by this method when compared with the conventional pulse-echo method.

2.1.4.3 P-scan UT

The new P-scan technique (Projection image Scanning technique) developed by the Danish Welding Institute represents a remarkable step forward towards a more reliable, more operator independent and more reproduceable ultrasonic inspection of welds.

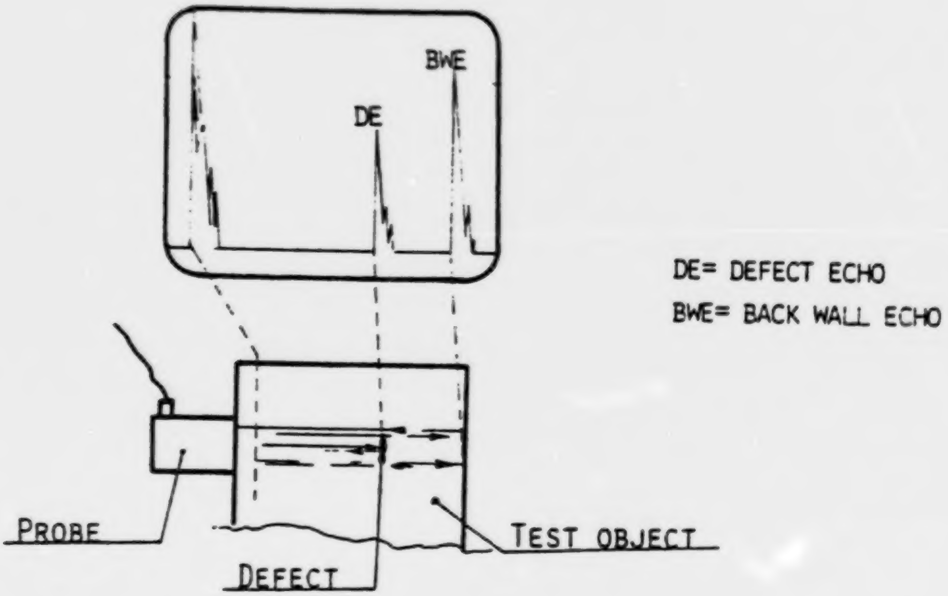

BWE
DE
DE= DEFECT ECHO
BWE= BACK WALL ECHO
PROBE
TEST OBJECT
DEFECT

Figure 2.6 The Pulse-Echo Principle [2.3]

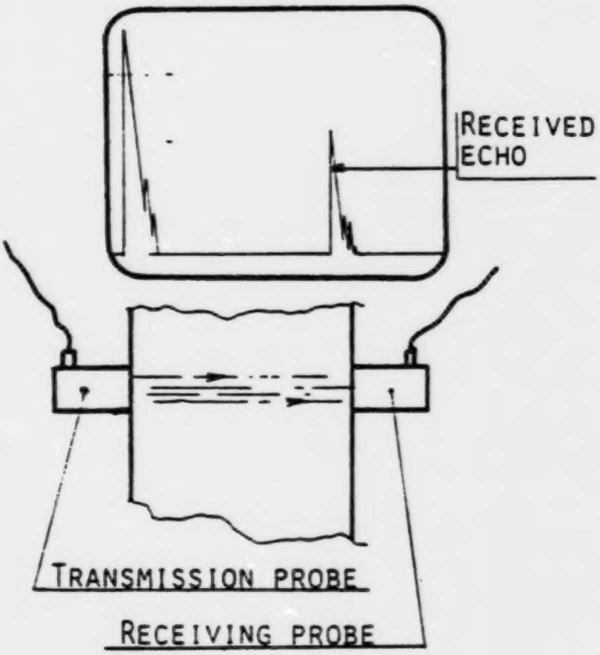
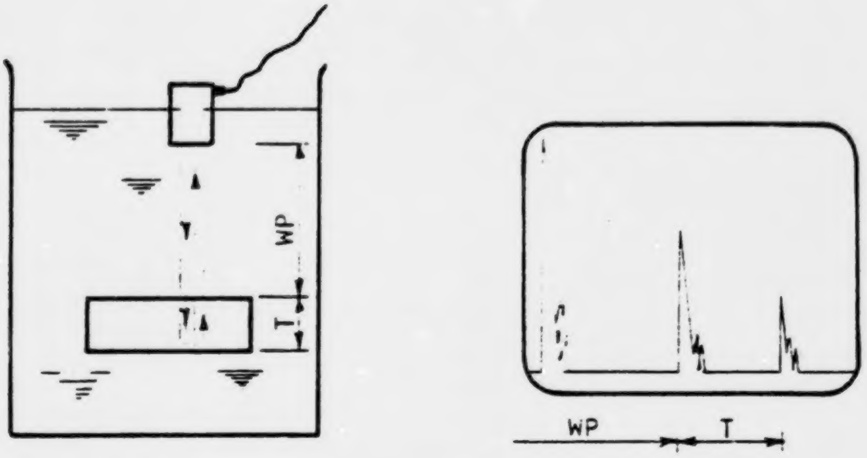

RECEIVED ECHO
TRANSMISSION PROBE
RECEIVING PROBE

Figure 2.7 The Transmission Method [2.3]



WP= WATERPATH

Figure 2.8 The Immersion Method 2.3

In the P-scan technique, echoes from weld defects are measured with one dB resolution and recorded together with the corresponding defect positions. Defect positions are then visualized as a projection of the defects on one or more projection planes. Usually two projection planes are used: one parallel to the surface and another plane normal to the surface parallel to the weld. Thus, defects appear as a top view and a side view. By using two projection planes, a complete three dimensional location of weld defects is obtained. In addition, all the maximum echo amplitudes along the weld are displayed in a logarithmic scale.

2.1.4.4 Probes

When testing materials with ultrasound, three types of probes can be used: the normal probe (longitudinal waves); the angle probe (transverse waves); and the double crystal probe.

Normal probe

A normal probe generates longitudinal waves and transmits them (via a couplant such as oil, grease or water) into a test object in a direction normal to the plane of the surface to which the probe is applied. The pulse propagates in a straight direction, but owing to beamspread, the sound field from the probe will become cone-shaped. The angle of beamspread is related to probe diameter and frequency. Using normal probes, Figure 2.9 illustrates how the multiple-echo technique may be used to measure material thickness. Note also that the echo height on the screen decreases as the length of the sound path increases.

A method which is suitable for sizing large defects with normal probes is the 6 dB-drop method, also called the half-value-method, Fig. 2.10. When a defect is detected, the probe is moved towards the edge of the defect until the defect echo height is reduced by 6 dB (or 50%), and the center of the probe is marked as the edge of the defect. By moving the probe around the defect in this fashion, the extent can be plotted. The same technique can be used with angle probes described below.

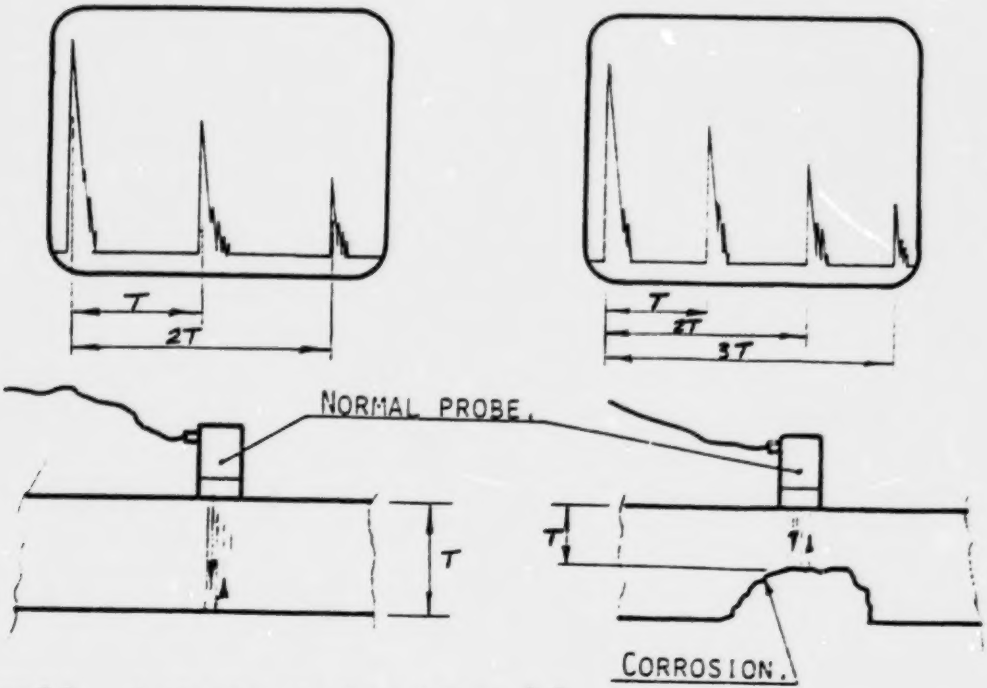

T
2T
T
2T
3T
NORMAL PROBE.
T
T
CORROSION.

Figure 2.9 Application of a Normal Probe 2.3

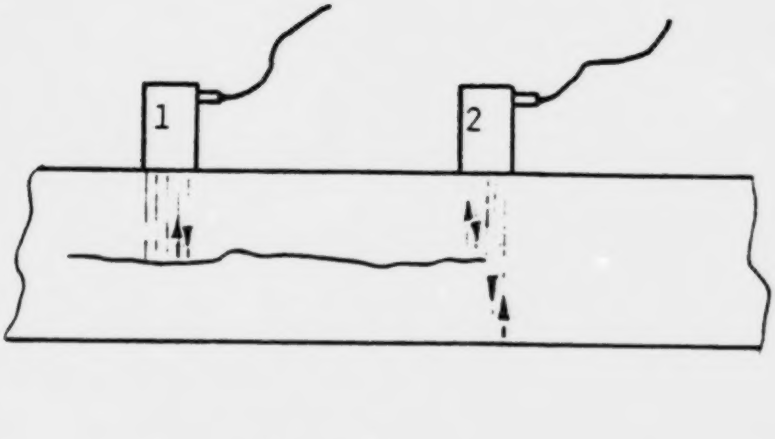


Figure 2.10 Determination of Flaw Size 2.3

Angle probe

An angle probe consists of a longitudinal wave element cemented to a wedge of plastic (perspex etc.) at an angle, see Fig. 2.11. If the wedge is applied to a material via a couplant, the wave will be refracted into the material at an angle. The refracted wave is a shear (transverse) wave and commercial shear wave probes are usually marked with the angle of shear wave in steel. Table 2.1 gives the angles of refraction in different materials for angle probes having an angle of incidence of 35-80 degrees with respect to steel. The sound field from the probe will appear cone-shaped as for the normal probe and the angle of beam spread can be calculated when the dimensions of the piezo-electric element and the frequency are known.

Double crystal probe

A double crystal probe (Fig. 2.12) consists of two separated piezo-electric elements (a transmitter and a receiver) at an angle (1 degree - 5 degrees) to the normal. The elements are cemented to plastic blocks (perspex etc.) and separated by cork insulation. Since the initial pulse must pass the acoustic delay block before reaching the contact surface of the material, it will not interfere with defects immediately below the contact surface. Hence, the dead zone will be greatly reduced.

TABLE 2.1

BEAM ANGLES OF REFRACTION[2.3]
(in Degrees)

Steel	35	45	60	70	80
Aluminium	33	42.5	55.5	63.4	69.6
Copper	23.6	29.7	37.3	41	43.5
Cast Iron	23	28	35	39	41

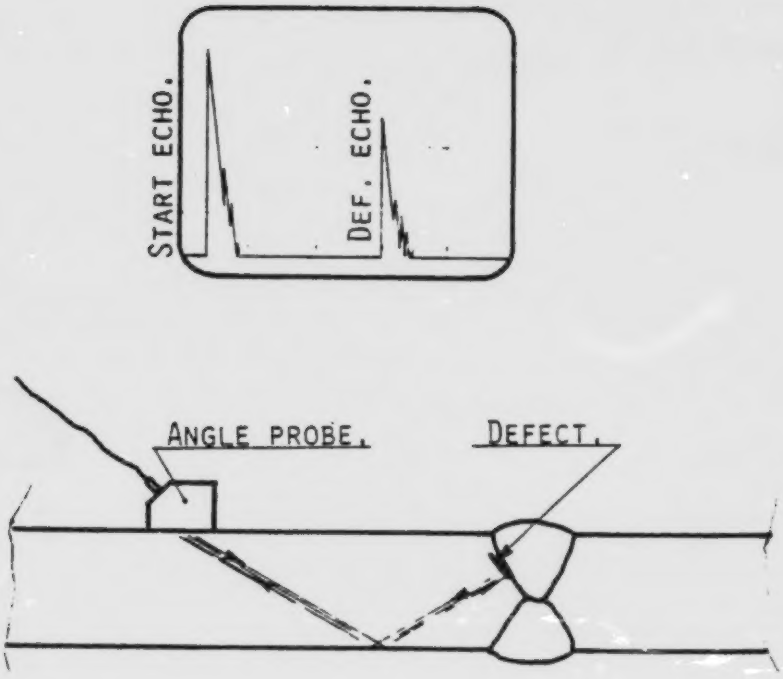

START ECHO.
DEF. ECHO.
ANGLE PROBE.
DEFECT.

Figure 2.11 Application of the Angle Probe 2.3

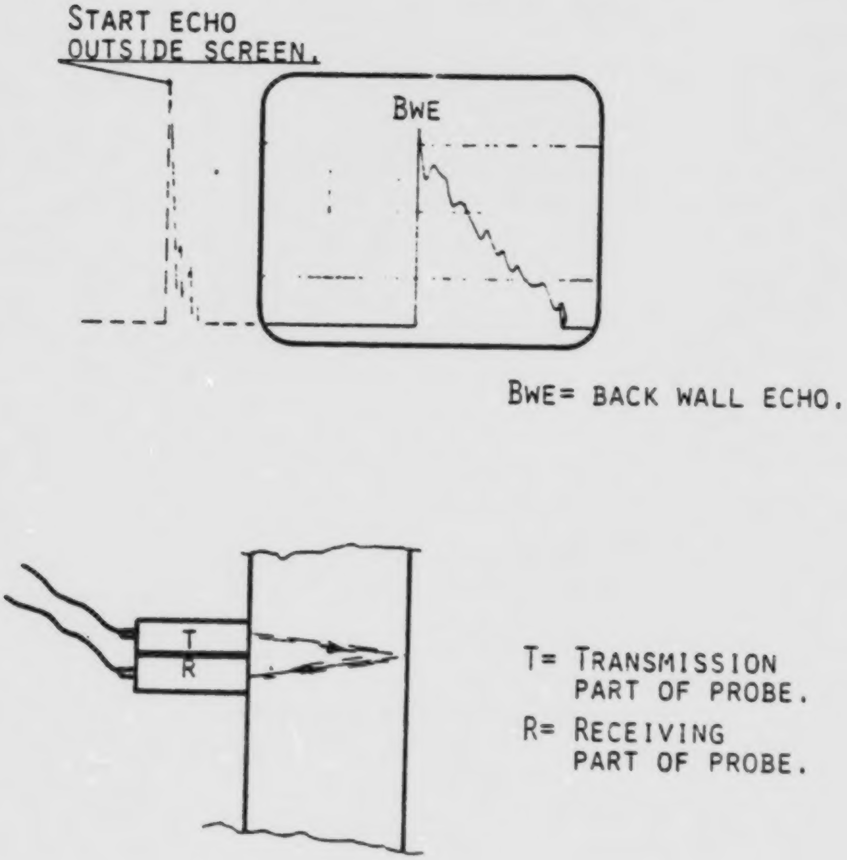

START ECHO
OUTSIDE SCREEN.
BWE
BWE= BACK WALL ECHO.
T
R
T= TRANSMISSION
PART OF PROBE.
R= RECEIVING
PART OF PROBE.

Figure 2.12 Principle of the Double Crystal Probe 2.3

An ultrasonic pulse from the transmitter element will propagate via the delay block into the material; reflected pulses from defects will reach the receiver element resulting in a defect echo on a CRT screen. The delay block and separate transmitter-receiver configuration, make the double crystal probe useful for detecting defects immediately below the contact surface and for measuring thicknesses within the range 1-30 mm.

With a double crystal probe, the first echo is always used for registration. This increases the detection efficiency close to the surface of the material and prevents multiple echoes from reaching the receiver.

2.1.5 Radiographic Testing (RT)

Radiography is an NDE technique used in examining volumetric (three-dimensional) weld defects such as pores, slag inclusions, slag lines, incomplete penetration, etc. For the underwater application, RT is typically used to test repaired welds and pipeline tie-in welds.

2.1.5.1 Principle of RT

Using RT, the image of the tested area, produced by the passage of a radiation beam through the test object is recorded on film for permanent documentation (Fig. 2.13). Thus, film interpretation is performed by a qualified NDE technician on the surface.

Radiographic testing can be performed using two types of radiation:

- x-rays, which are produced electrically by an electron beam in a high voltage electric tube;
- γ-rays, which are produced by the decay of radioactive material such as Cobalt 60 or Iridium 192. When applied below water, γ-ray equipment is preferred due to the hazardous high voltage of the x-ray source.

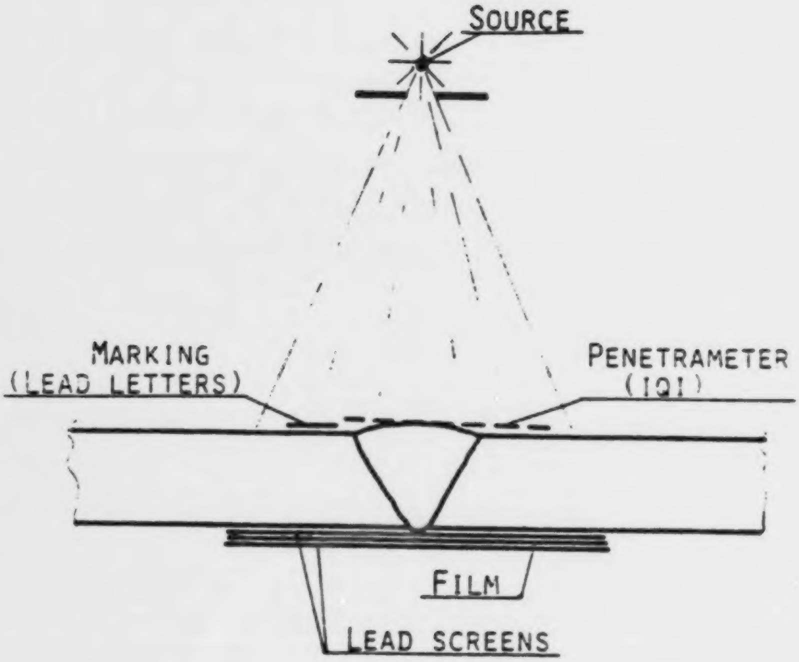

SOURCE
MARKING
(LEAD LETTERS)
PENETRAMETER
(IQI)
FILM
LEAD SCREENS

Figure 2.13 Radiographic Weld Examination 2.3

The penetrating power of radiation is a function of its energy. Depending on radiation energy, for example, radiographic testing can be used on material thicknesses equivalent to more than 100mm of steel. The energy of the radiation from radioactive isotopes is characteristic for each isotope and remains constant throughout the lifetime of the isotope. The energy of Iridium 192 radiation corresponds to an x-ray voltage of about 800 kV. For Cobalt 60 the corresponding x-ray voltage is approximately 3000 kV.

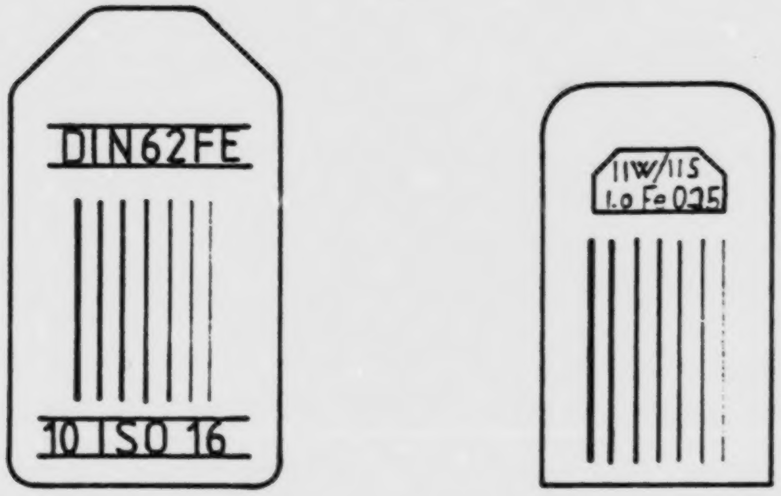
In order to determine the sensitivity of a radiograph, a penetrameter or image quality indicator (IQI) is used, Fig. 2.14, the most frequently used IQIs being ASME hole penetrameters.

2.2 Inspection Equipment

Descriptions and specifications of NDE equipment are presented in Appendix A. The equipment described is used in the following techniques:

- visual inspection;
- methods based on electromagnetism including MPI, Magfoil, magnetography and EMD;
- AC potential drop;
- ultrasonic testing including, thickness measuring devices, flaw detection and sizing devices, Corroscan and Ultrasonic Torch;
- radiographic testing; and
- remotely operated vehicles and atmospheric submersibles.

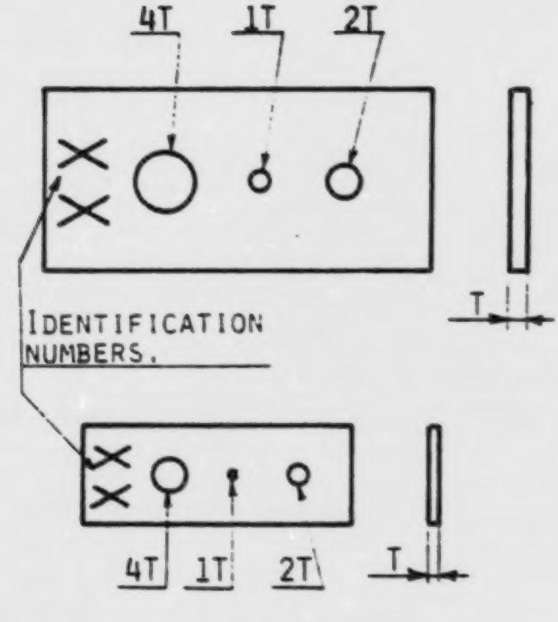
Selected manufacturers of equipment for the techniques listed above are included in Table 2.2.


DIN62FE
10 ISO 16
IIW/115
1.0 Fe 025

DIN I.Q.I.

IIW I.Q.I.

a) DIN and IIW Penetrameters


4T
1T
2T
IDENTIFICATION NUMBERS.
T
4T
1T
2T
T

b) ASME Penetrameter

Figure 2.14 Typical Penetrameters [2.3]

TABLE 2.2
SELECTED LIST OF MANUFACTURERS OF OFFSHORE NDE EQUIPMENT

	NDE Method					
Company	Visual	Electro-magnetism	ACPD	UT	RT	Other
Baugh & Weedon				+		
B.I.X.					+	
Danish Welding Institute				+ (pipelines)		
Henrichs & Walther		+ (Magfoil)				
I.S.E.						+ (ROVs)
Krautkramer-Branson				+		
Magnetische Pruefanlagen		+ (magnetography)				
Nikon	+					
Nortec				+		
Oceaneering						+ (Diving support)
OIS		+ (MPI)		+	+	
OSEL	+	+ (MPI)	+			
Panametrics				+		
RTD				+ (pipelines)		
Sonic Instruments				+		
Thorburn Technics		+ (EMD)				

2.3 Assessment of NDE Methods and Equipment

In this section the NDE methods and equipment already described will be assessed on the basis of information obtained for the study and on the following criteria:

- application; addressing construction type and detail, type of defects anticipated, operation mode;
- accessibility; addressing weather conditions, water depth and currents, visibility, coatings, marine growth, structural geometry and inspection zone;
- reliability; addressing both procedures and equipment;
- cost; addressing cost components and cost reducing measures.

The assessment will also contain recommendations which would improve the performance of the methods.

2.3.1 Visual Inspection

The complexity of work, depth of water, risk and economics must be evaluated on a project specific basis to determine the best method for visual examination. Because of the rapid emergence of underwater technology, it is normally necessary for operators to do their own evaluations in close consultation with diving companies and ROV operators. Demonstrations, testing, and previous performance records are all used to help make choices. Because ROV's, manned submersibles and similar equipment are often purpose designed, comparative evaluations are not meaningful without first knowing the detailed requirements of the job.

To illustrate reliability of visual inspection, the results of a Shell Expro experiment are presented[2.8]. The trials were performed on 6 T-nodes varying in size from 6 in. to 18 in. diameter chord and 3 in. to 18 in. brace. NDE testing was conducted in a steel tank having dimensions 7 m long x 4 m wide x 3 m high. Fatigue cracks of between 5 mm and 610 mm long were introduced in several nodes. It can be inferred from data in Table 2.3 and 2.4 that the average successful detection of surface cracks found in the cleaned nodes was 23% with a standard deviation of 19% compared to 79% in the uncleaned nodes with a standard deviation of 8%. This large difference of detection probability and sizing may have been attributable to the fact that the uncleaned nodes had larger proportion of the large cracks.

It can be concluded from the data in Tables 2.3 and 2.4 that visual inspection of node welds is unreliable for smaller cracks (up to approx. 200mm), but it can provide reliable results when monitoring critical modes for structural integrity (large, open fatigue cracks).

These is an increasing tendancy to reduce the overall dependency on the diver or underwater examiners' interpretations of the visual data. Rather, it is relayed to the surface support group where it is viewed and evaluated by appropriately trained personnel who are not encumbered with having to cope with the underwater environment. Still photography, and even more important, audio and video transmissions in real time are rapidly improving diver effectiveness. These improvements facilitate the use of simple and effective ways of recording visual and audio information for future detailed and comparative evaluations and documentation. There is also a need for improvements in the following areas to enhance the visual inspection technique:

- stereo photography and stereo video recording;
- fibre optics for close visual examination;
- surface monitoring;
- recording and documentation;
- imaging systems optical or acoustical, for waters with low visibility.

TABLE 2.3

DISTRIBUTION OF CRACK SIZES[2.8]

Size (mm)	0-10	11-20	21-40	41-100	101-200	201+
Cleaned Nodes (Nos. 1,2,3,4)	4	2	4	1	3	0
Uncleaned Nodes (Nos. 5,6)	0	2	4	1	1	5
Total	4	4	8	2	4	5

TABLE 2.4

INDIVIDUAL DIVER PERFORMANCE ON VISUAL INSPECTION[2.8]

	Diver No.			
	1	2	3	4
Nodes 1,2,3, and 4 (Cleaned)				
Total length of cracks to be detected	666mm	666mm	666mm	666mm
Actually detected	270mm	290mm	41mm	0mm
Percentage Success	41%	44%	6%	0%
Uncorrelated Defects	190mm	269mm	612mm	0mm
Percentage Uncorrelated to Total length to be detected	29%	40%	92%	0%
Nodes 5 and 6 (Uncleaned)				
Total length of cracks to be detected	2551mm	2551mm	2551mm	2551mm
Actually detected	2180mm	2258mm	1816mm	1785mm
Percentage Success	85%	89%	71%	70%
Uncorrelated Defects	150mm	226mm	115mm	238mm
Percentage Uncorrelated to Total length to be detected	6%	9%	5%	9%

In summary, visual inspection regardless of whether it is conducted using divers, personnel in submersibles, controlled atmosphere suits or remotely operated vehicles, should be considered as a primary, general investigation method. It is effective and fundamental for assessing the general condition of underwater structures, locating gross defects and in some cases determining the necessity for more detailed examination. The underwater environment produces a very broad range of psychological and physiological stresses on the human operator. It adversely affects human sensory perceptions, especially visual activity. Hence, the need arises to assist the underwater operator by designing his tasks to be simple and primarily non-interpretive .

2.3.2 Methods and Equipment Based on Electromagnetism

2.3.2.1 MPI

The previously mentioned Shell Expro Experiment[2.8] also evaluated the performances of divers using MPI equipment. Eight divers participated and four different magnetization methods were used. Tables 2.5 and 2.6 summarize collective and individual results. It was discovered that while there was a high and consistent level of crack detection ($\bar{x}$= 90% and σ= 8%), there was also a high incidence of uncorrelated results ($\bar{x}$=40% and σ=44%). It was further reported that no significant differences in equipment types could be found. However, the highest success in locating cracks was achieved using the closed loop conductor and a permanent magnet. The permanent magnet was used in combination with parallel conductors to detect and confirm small cracks. With permanent magnets, only small parts of the weld could be covered because the poles were very close. The advantages in using permanent magnets are that there is no electric supply and both weight and size allows easy handling for the diver, however there are several disadvantages as well:

- as a result of the static magnetic field induced by permanent magnets, the test area must be entirely magnetized to saturation before the leakage field from small defects will be detectable;

TABLE 2.5

SUMMARY OF MAGNETIC PARTICLE INSPECTION RESULTS[2.8]

Node and Crack Identification (Size)	Detection Success	Total Length of Cracks to be Detected	Actually Detected	Uncorrelated Defects Reported
Node Ref. No. 1				
1-0 (185mm)	5 out of 5	925mm (100%)	805mm (87%)	245mm (27%)
Node Ref. No. 2				
1-0 (110mm)	5 out of 5	600mm (100%)	550mm (92%)	752mm (125%)
2-0 (10mm)	3 out of 5			
Node Ref. No. 3				
1-0 (88mm)	19 out of 19	3211mm (100%)	2838mm (88%)	1557mm (48%)
1-1 (5mm)	16 out of 19			
1-2 (10mm)	16 out of 19			
2-1 (20mm)	19 out of 19			
2-2 (23mm)	19 out of 19			
2-3 (15mm)	16 out of 19			
3-0 (8mm)	3 out of 19			
Node Ref. No. 4				
1-0 (110mm)	13 out of 13	2496mm (100%)	2139mm (86%)	132mm (5%)
1-1 (26mm)	10 out of 13			
1-2 (32mm)	11 out of 13			
1-3 (24mm)	11 out of 13			

TABLE 2.6

INDIVIDUAL DIVER PERFORMANCE ON MAGNETIC PARTICLE INSPECTION[2.8]

	Diver No.							
	1	3	4	5	6	7	8	9
Nodes 1,2,3 and 4								
Total length of cracks to be detected (mm)	1332	1183	914	1613	666	666	192	666
Actually detected (mm)	970	1045	802	1471	635	561	189	659
Percentage Success	73%	88%	88%	91%	95%	84%	98%	99%
Uncorrelated Defects (mm)	29	63	1115	341	618	75	1	444
Percentage Uncorrelated to Total length to be detected	2%	5%	122%	21%	93%	11%	0.5%	67%

Note: Diver No. 2 did not undertake MPI.

- few permanent magnets can meet the requirement of a tangential field strength of 2400A/m which is accepted as a minimum magnetization requirement;
- actual magnetization of the test area is difficult to measure;
- it is difficult to ensure good contact between the pole pieces of the magnet and the component being tested.

No correlation was found between using various magnetic particle inks and probability of crack detection[2.8].

There is more operational experience with MPI than with any other NDE method. Magnetic particle inspection using prod magnetization has been applied under DnV's supervision during annual inspection of steel structures in the North Sea since 1975. However the prod magnetization method has been found difficult to use[2.8]; specifically, maintaining good contact causes some problems.

In the 35 jacket structures that were reviewed by DnV[2.9], magnetic particle testing had been performed at least once on 382 joints. This represented a selection of about 5% of the total number of joints in the structures. A total of 25 cracks were found in 18 joints as shown in Table 2.7.

Surprisingly the smallest crack reported was 6mm long and only three joints were repaired. All the cracks reported were confirmed by surface grinding to penetrate at least 1mm into the material.

A disadvantage of magnetic methods is the inadequate definition of detected defects. Only the length of the defect is indicated whereas the depth is usually the most critical dimension. The use of crack-depth indicators would therefore increase the reliability of the method.

TABLE 2.7

CRACKS OBSERVED AND REPAIRED[2.9]

Crack length in mm	Number of Cracks observed	Number repaired
6-25	10	-
26-50	4	-
51-100	1	-
101-200	7	-
200-940	3	3

Cracks detected by MPI in 35 North Sea Structures 1975-79.

The following improvements are suggested for magnetic methods:

- development of methods suitable for ROV operations;
- alternative detection media with the permanent recording of results combined with crack depth measurements.

2.3.2.2 Magnetography

The magnetographic method has been used for over ten years in the steel industry for fillet testing and continuous weld testing on tubes.

The Magneto Marine Method was first used for underwater inspection of four platforms in the Danish sector of the North Sea in 1977. Due to lack of wider experience with the method, the findings obtained by this technique should be confirmed by conventional MPI method. Preliminary results however indicate that the results obtained are objective, reliable and reproducible[2.5].

2.3.2.3 EMD

The reliability of Electro-Magnetic Detection should be evaluated in the light of the following characteristics:

- no detection probabilities are documented;
- depth estimation of shallow cracks is to a certain extent possible;
- material properties (welds) and geometry (including weld surface geometry) will influence the detection and characterization of defects;
- operational difficulties at the present stage of development.

Limited trials with EMD equipment have been reported. The advantages of EMD as claimed by Thorburn Technics International are:

- no need for removal of such coatings as paint, mud, dirt, rust or slime;
- can be used on rough surfaces;
- can be used both above and underwater;
- system is easy to calibrate and operate.

However, underwater inspection trials using TTI's Mk III Deep Sea are still in progress. Therefore, until more experience is gained, the use of EMD equipment should be limited to a pre-testing on undressed surfaces with MPI back-up of any findings.

2.3.3 ACPD Measurement

The ACPD method has been used for crack propagation monitoring and for inservice crack depth measurements on offshore steel structures both above and below water.

The method was first calibrated in the laboratory for tubular joint fatigue testing[2.7], Fig. 2.15, where an accuracy of at least ± 2mm was obtainable for underwater applications.

For the fatigue of welds in heavy plates of thicknesses up to 100 mm, the method resulted in an underestimation of the crack depth of typically 10-20%, Fig. 2.16.

Crack measurements close to crack edges also led to a systematically overestimated measured value. The required correction factor is a function of the crack depth and the distance from the edge. It can be seen from Fig. 2.17 that, within the crack depth range of 1 to 30 mm, the edge effect will be insignificant if the depth measurement is performed more than 40 mm away from the edge.

Tests$^{2.10}$ were also done on curved surfaces, Fig. 2.18. Results from measurements on pipes of 161 mm and 212 mm respectively are shown in Fig. 2.19.

ACPD equipment calibrated for measurements on flat plate, requires a correction factor when taking crack measurements in a corner, Fig. 2.20. The deviation between measured and nominal crack depth can be calculated approximately according to:

$$\Delta d = \frac{L}{2} \left(\frac{1}{\sin\alpha/2} - 1 \right) \qquad (1)$$

where α = corner angle
L = electrode spacing

The corrected depth of a crack in a corner is thus given by:

$$d = d_{\text{measured}} - \Delta d \qquad (2)$$

Fig. 2.21 shows results of depth measurements in a 120 degree corner when the crack depth indicator has been calibrated for a flat plate. The deviation between nominal and measured value is between 0.7 mm and 1.3 mm. This is in fair agreement with the calculated deviation of +0.8 mm (α= 120 degrees, L = 10 mm).

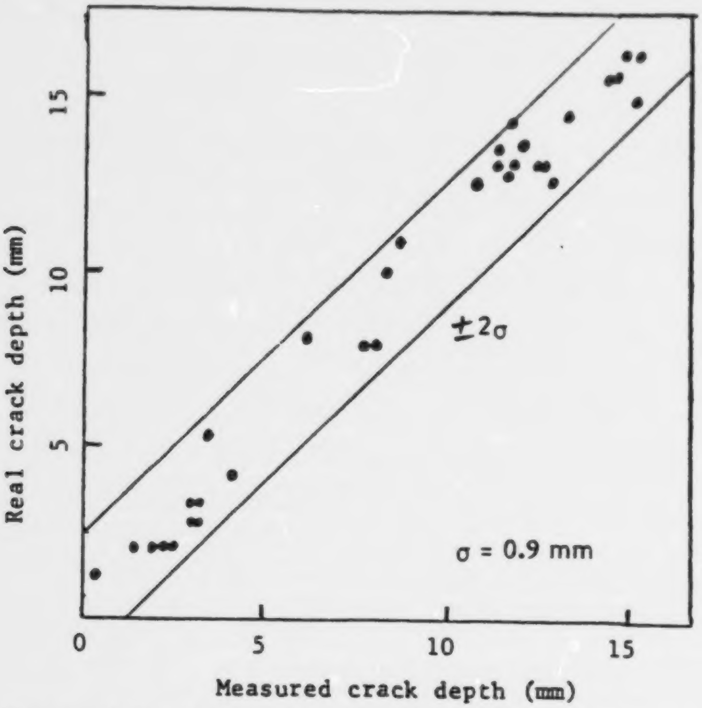


Figure 2.15 Measured Crack Depth Values compared with the results from Destructive Examinations for Fatigue Cracks located at the Weld Toe in a Tubular T-Joint. The Standard Deviation is 0.9 mm and the Mean Deviation is -0.6 mm 2.7

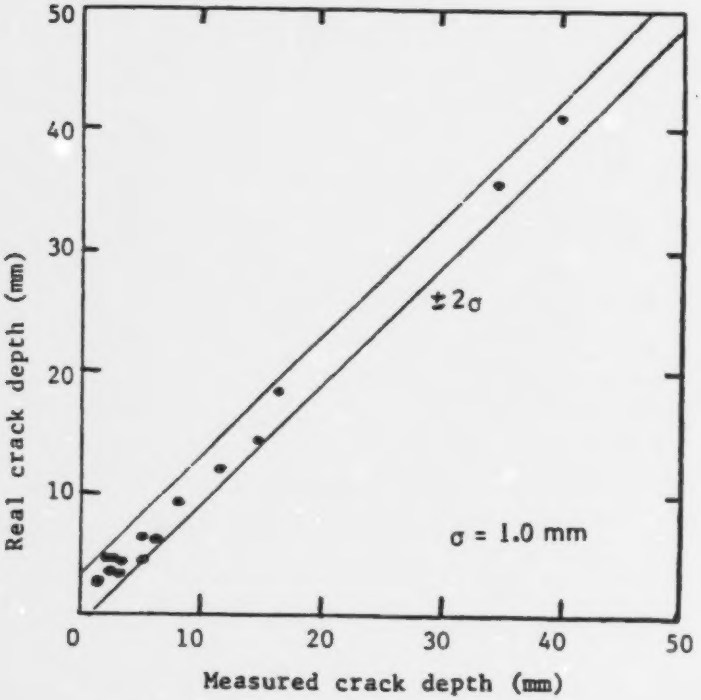


Figure 2.16 Measured Crack Depth Values compared with the Crack Profile Measurements for Fatigue Cracks located at the Weld Toe of the Welds in 100 mm Plates. The Standard Deviation is 1.0 mm and the Mean Deviation is -1.0 mm 2.7

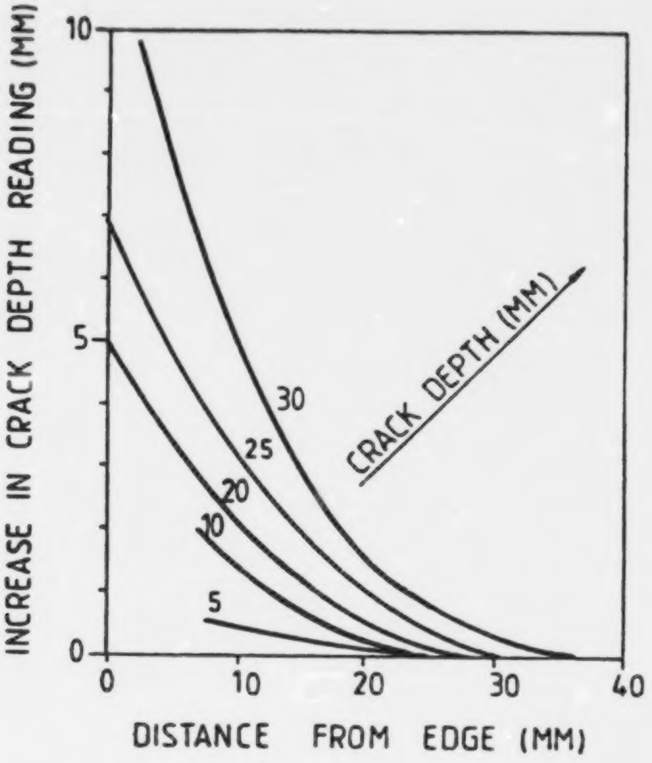


Figure 2.17 Correction Curves for Crack Depth Measurements Close to an Edge 2.10

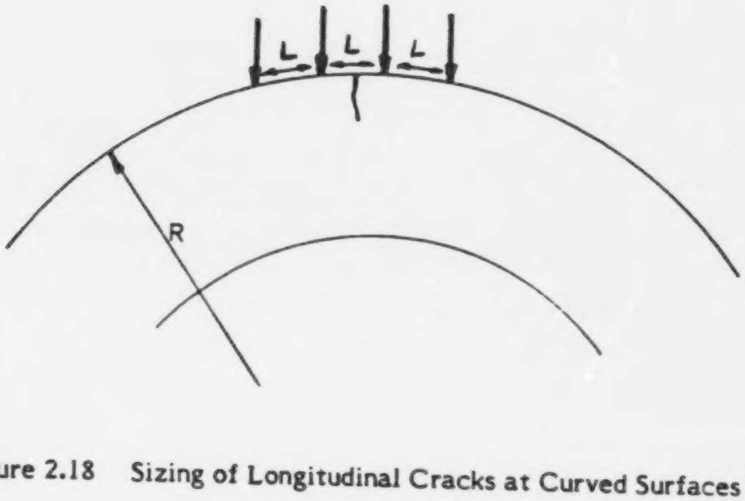


Figure 2.18 Sizing of Longitudinal Cracks at Curved Surfaces 2.10

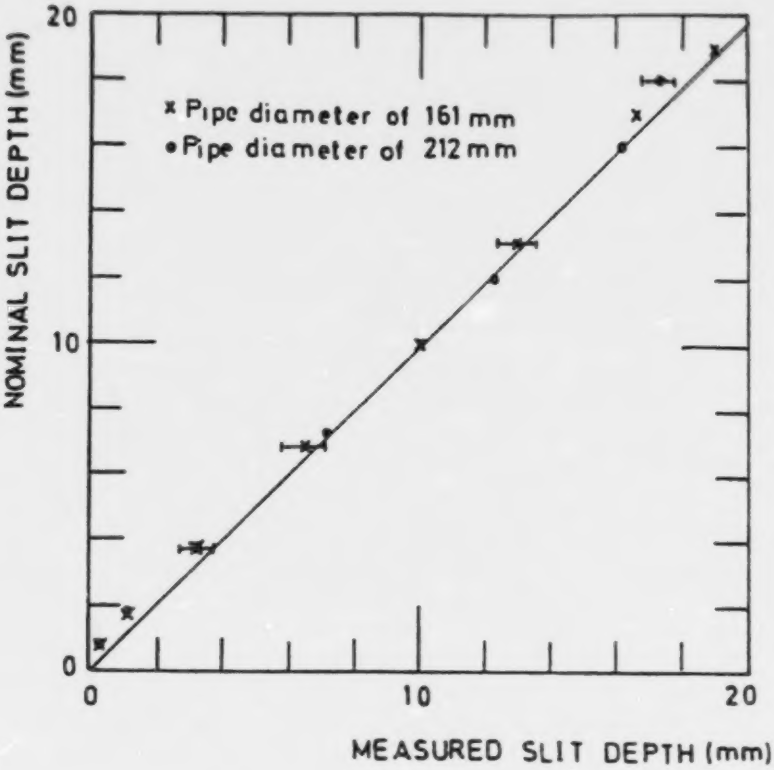


Figure 2.19 Sizing of Slits at Curved Surfaces with the Equipment Calibrated at Plane Surface 2.10

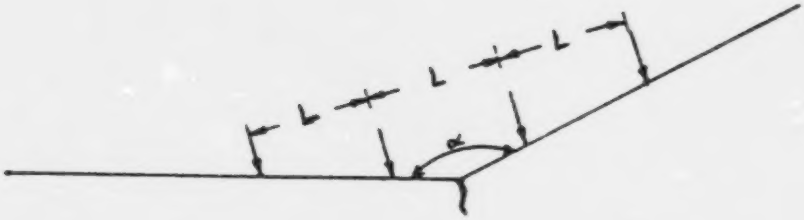


Figure 2.20 Sizing of Cracks in Corners 2.10

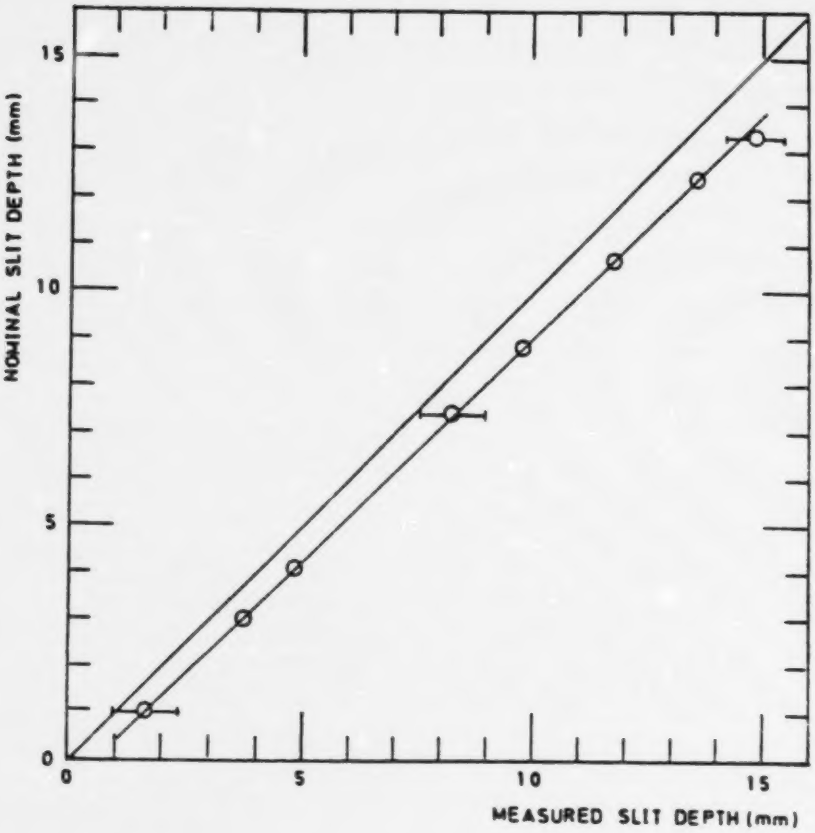


Figure 2.21 Nominal and Measured (not corrected) Slit Depths in a 120° Corner containing a Weld with some Irregular Surface 2.10

Calibration measurements were also done for various length-to-depth ratios (aspect ratios) in order to establish correction curves, Fig. 2.22. These curves shall be used when the crack initially measured depth exceeds 20% of the crack length. If the crack depth exceeds 50% of the crack length, the present crack sizing technique will give no relevant information about the crack depth.

2.3.4 Ultrasonic Testing

The principal application of ultrasonic techniques is flaw detection and sizing, and thickness measurement. Ultrasonic testing has several advantages though its underwater application is still limited. These are:

- high sensitivity, permitting detection of minute defects;
- great penetrating power, allowing examination of extremely thick sections, e.g. up to 10m of steel;
- accuracy in the measurement of flaw position and estimation of flaw size;
- fast response, permitting rapid and automated inspection;
- may be performed with access to only one surface of the object.

The reliability and efficiency of improvement of ultrasonic methods would be enhanced by improvements in respect of the following:

- documentation systems;
- ultrasonic pigs for riser and pipeline inspection;
- automated corrosion- and weld-inspection equipment from diver assisted to use by ROV;
- defect sizing by use of the time-of-flight technique, also for continuous monitoring;
- measurement of material stresses;

and possibly the use of

- acoustic holography or other advanced ultrasonic techiques.

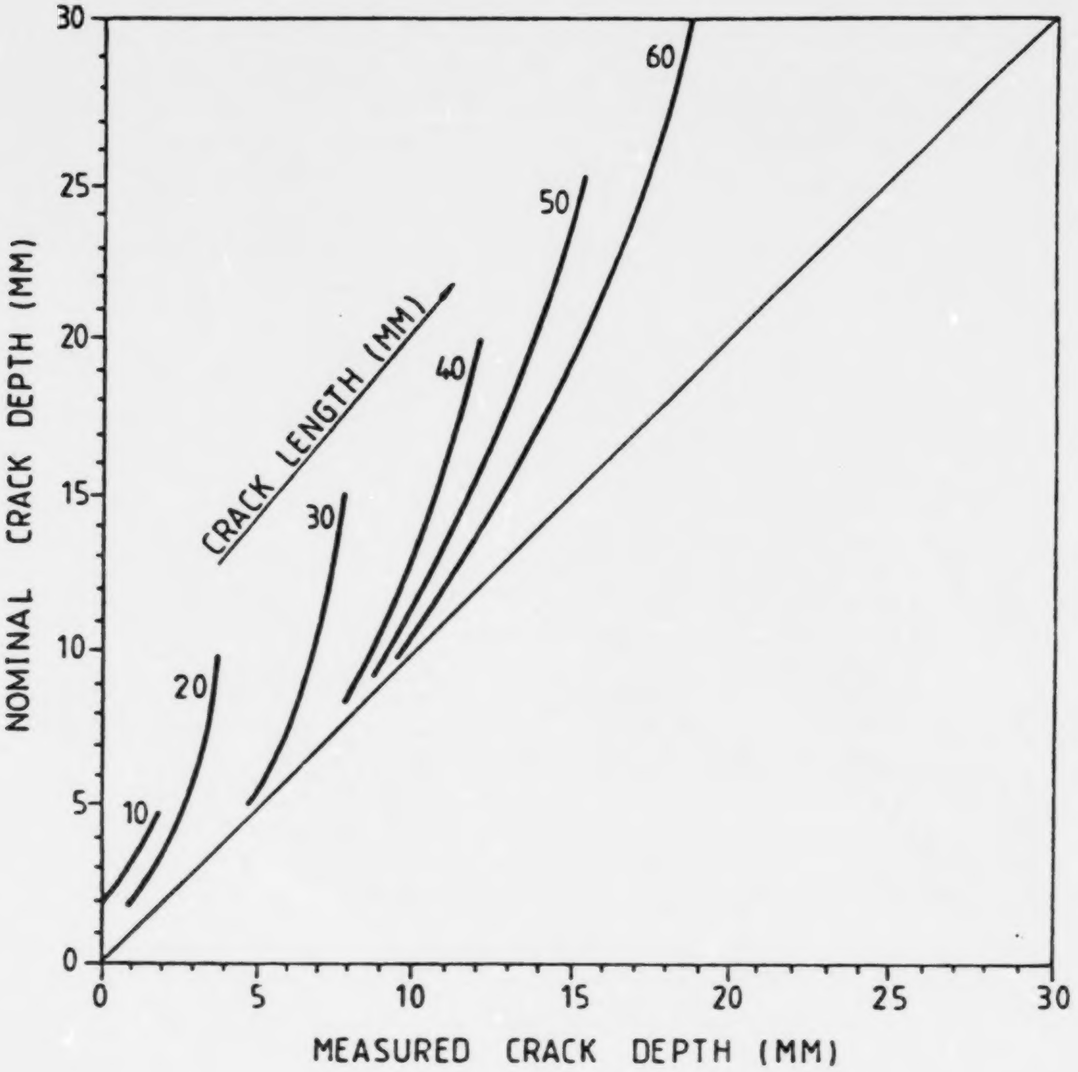


Figure 2.22 Correction Curves for Short and Deep Cracks 2.10

No ultrasonic examination is today performed on concrete structures below water. If needed, it is, however, possible to develop ultrasonic techniques for crack depth and concrete quality measurements.

Test conditions which may limit the application of ultrasonic methods usually relate to one of the following factors:

- unfavourable sample geometry of test object (e.g. complicated tubular joints);
- undesirable internal structure; for example grain size, structure porosity, inclusion content, or fine, dispersed precipitates. Examples of materials difficult to test by ultrasonics are austenitic steel and welds involving nickel base alloys. Penetration of sound into these materials is limited and interpretation of results can be difficult;
- coupling and scanning problems;
- due to high sensitivity, false or irrelevant indications may occur. Type of defect may be difficult to specify;
- operator's qualifications in manually performed UT.

The limitations are also the major source of uncertainties in the UT results.

To illustrate these limitations, the U.K. Welding Institute performed well controlled laboratory tests to compare the performance of various UT techniques[2.11]. Some results of this study are presented in Table 2.8. There is a distinct tendency to underestimate the crack depth using UT and also a considerable scatter in the results is noticeable. One would have to add 7-8 mm to the measured flaw size to obtain a 97.5% confidence limit on the maximum size of the actual defect which seems to be too conservative[2.11].

TABLE 2.8

REVISED SIZE MEASUREMENT ACCURACY FOR PLANAR DEFECTS[2.11]
(maximum reported size compared with maximum actual size)

Tests	Mean error $\bar{x}$, mm	Standard deviation σ, mm	95% confidence limits $(\bar{x} \pm 2\sigma)$, mm	Sizing method
Manual operator 4MHz	-3.1	4.6	+6.1 -12.2	20dB drop, all angles
Laboratory 4MHz*	-3.5	4.1	+4.7 -11.8	20dB drop, 45 degrees
Laboratory 4MHz*	-3.6	5.6	+7.6 -14.8	20dB drop, 60 degrees
Laboratory 4MHz*	-2.3	4.5	+6.7 -11.2	20dB drop, all angles
Laboratory 2MHz*	-3.2	4.0	+4.8 -11.2	Maximum amplitude, 45 degrees
Time-of-flight	-0.5	2.2	+3.8 -5.0	Time measurement

* indicates that these data are not normally distributed

Performance of the operator is decisive for the reliability of manually performed UT. In Fig. 2.23, the acceptance curves for twelve ultrasonic operators were compared[2.12]. It can be seen that for a 12 mm deep crack the probability that this crack remains undetected can be as high as 60% by one operator or as low as 5% by another operator. The scatter around the average echo amplitude shows the following pattern in the uncertainties encountered[2.12]:

- operator/inspection uncertainties: 5dB
- defect/specimen variations: 3dB

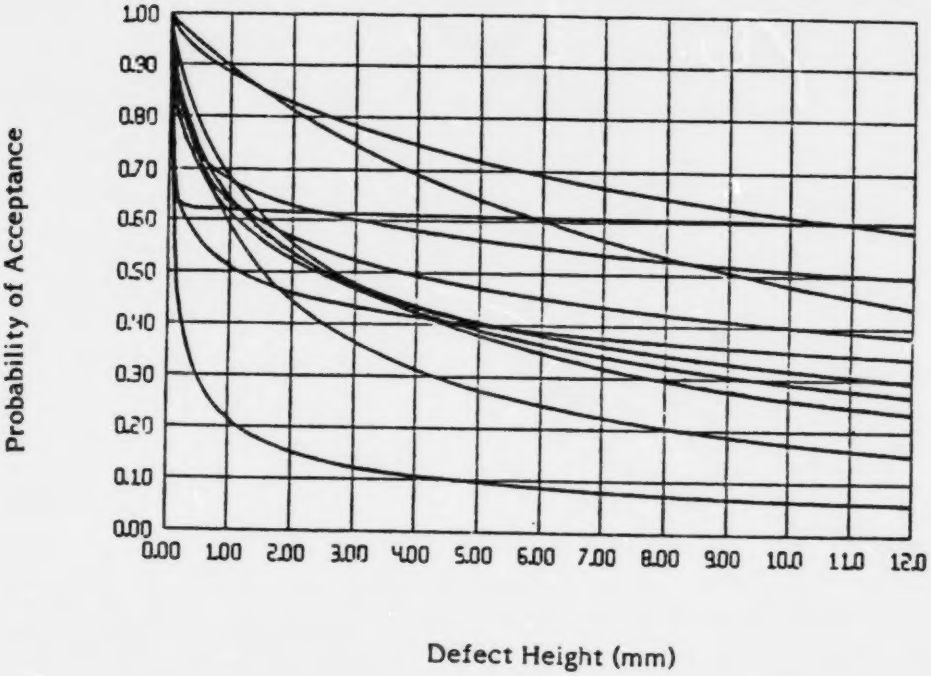


Figure 2.23 Acceptance Curves for 12 Different Ultrasonic Operators 2.12

These values also demonstrate that the main uncertainty stems from the operator.

The underwater use of manually operated UT equipment is prone to even more human error due to harsh environmental conditions. Partial solution to this problem is TV monitoring and surface CRT display so that the diver's interpretation would be limited.

More promising developments are based on automation, and computer control and data logging (Corroscan, P-scan) where the diver's involvement may be limited to the installation of the equipment.

2.3.4.1 Wall Thickness Measurements with UT

Wall thicknesses can be measured using normal, e.g. transmitter/receiver type probes. It is important to be aware of the possibility of erroneous measurements due to a possible water (or paint) layer between probe and object. In general A-scan type equipment gives more reliable readings under all conditions as it allows for better interpretation of the echoes and the echo pattern including the use of multiple echoes for thickness determination. Digital wall thickness meters are, however, usually smaller and easier to handle, but require a smooth, flat surface for reliable use as they usually rely on elapsed time to the first back wall echo for the thickness measurement. This may require grinding of the surface to bare metal even in the case of very modest surface corrosion. It is further recommended that at least 3 individual measurements be taken and reported from each measuring point and that spurious readings also be reported.

For wall thickness measurements the readout or recording equipment may be kept above water, provided there is a satisfactory communication system between diver and surface interpreter and that an adequate system for determination of measurement position has been established.

The accuracy of wall thickness measurements is about 0.5-1.0mm in corroded areas and may improve to 0.1mm on very smooth surfaces.

Automatic recording of internal corrosion has an accuracy of about 0.5mm (standard deviation) in the measured wall thickness and a high degree of reproducibility with a lateral resolution better than 2.5mm.

Manual ultrasonic weld examination is difficult and timeconsuming to perform under water.

2.3.4.2 Corrosion Pit Measurement

Conventional ultrasonics will not function on pit-corroded surfaces because of spurious signals caused by scattering.

The Southwest Research Institute (SWRI) developed a computer-controlled system using a focused transducer concept. The scanning of the transducer over the corroded plate and its alignment over the pit center are performed automatically by the high-speed data acquisition system. Pattern analysis is used to reject wave forms with high probability of having a spurious signal instead of a back-surface reflection. The average error in the thickness measurements was 4%. The system was developed for underwater use and successfully tested on harbor H-pile structures[2.13].

2.3.4.3 Corroscan

The Corroscan system has been operated in the North Sea since June 1981 and a large number of risers and pipelines have been successfully inspected in selected areas[2.14].

The Corroscan system, developed by DnV, has the following applications and benefits:

- complete mapping of selected areas of submerged pipelines and risers, horizontal and vertical sections OD 10-3/4" and larger. Bend sections with radius of curvature greater than 32" (3D bend for a 10-3/4" pipe);
- storage of all data for more comprehensive analysis onshore and comparison with possible re-inspection data;

- on-site calibration, storage of calibration data;
- reproducibility adequate for calculation of corrosion rates;
- no special ultrasonic training required for divers;
- high inspection speed compared to manual testing.

2.3.4.4 Ultrasonic Torch

The Ultrasonic Torch is a new system with little operational experience documented[2.15]. Trials have been carried out by divers with and without experience in ultrasonic testing with the result that the torch was easy to use. During the trials, the torch was used at depths of up to 120 m and it appeared that there would be no difficulty in using the torch at its design depth of 200 m.

2.3.5 Radiography

Although radiographic testing is by far the most commonly used method for above water weld examination, underwater applications are not common.

However, radiographic examination has several advantages, provided that a dry underwater habitat can be supplied:

- radiography will detect both surface and internal discontinuities which are volumetric in form;
- planar defects can be detected provided they are oriented parallel to the radiation beam;
- the radiograph provides a permanent record of the test which can easily be re-examined.

Despite the advantages of radiographic examination cited above, several disadvantages are also inherent:

- access to both sides of the test object is necessary to produce a radiograph;
- the shapes of the test object may make it difficult to produce a radiograph with useful information;
- discontinuities such as cracks, laminations, lack of fusion, etc., must be lined up with or parallel to the x-ray beam to be detected clearly;
- choice of radiation energy for a particular thickness of weld is a critical factor;
- personnel must be qualified. Proper interpretation of films requires extensive training and experience.
- x-rays and gamma rays are hazardous. Irradiation of the human body will increase the risk for developing cancer and genetic defects. Such radiation cannot be detected by any of the human senses and proper instruments must be used to check the radiation level. Due to the radiation danger, limitations may be imposed upon time and place of radiography;

A systematic investigation of the reliability of RT findings was performed as a part of the Nordtest Project No. 72-76[2.16].

A number of different types of defects were investigated[2.17]:

Porosity (A):	2
Lack of fusion (C):	10
Lack of fusion combined with lack of root penetration (CD):	12
Lack of root penetration (D):	36
Total number of defects:	60

The distribution of the height and types of the defects are shown in Fig. 2.24. The test plates were radiographed according to IIW Class B and the films interpreted independently by 2 radiographic interpreters according to IIW degree 1-5.

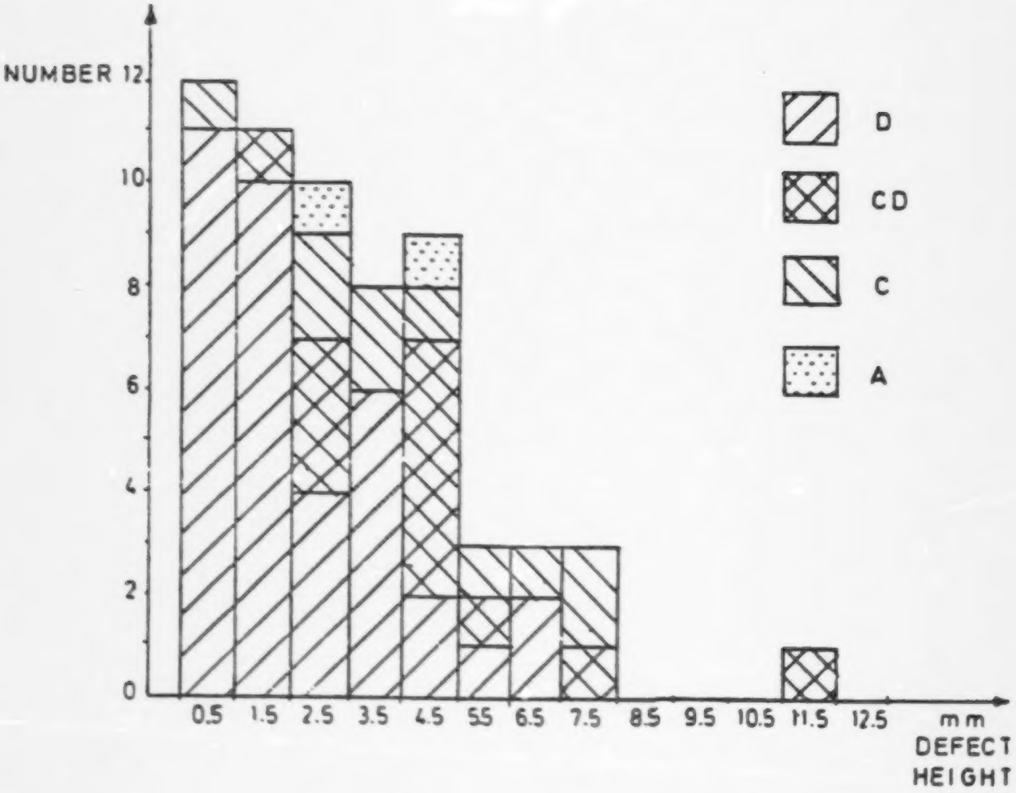


Figure 2.24 Distribution of Defect Height and Type 2.17

There is no obvious parameter to correlate with defect height from a radiograph. However, Fig. 2.25 shows the correlation between IIW degrees and defect height. Table 2.9 gives information on defect type estimated by using RT compared to the real defect type found by destructive testing.

TABLE 2.9
DEFECT TYPE ESTIMATED BY RT[2.17]

		Defect type estimated by RT				
True Defect Type		A	B	C	CD	D
Porosity	(A)	0.5		0.5		
Lack of Fusion	(C)	0.2	0.2	0.4		0.2
Lack of Fusion combined with Lack of Root Penetration	(CD)		0.1	0.3	0.0	0.6
Lack of Root Penetration	(D)	0.0	0.1	0.1		0.8

It can be seen from Table 2.9 that lack of root penetration (D) is estimated quite well by RT, giving correct defect type in 80% of the cases. A correct type estimation of lack of fusion (C) seems difficult (40%), whereas lack of fusion combined with lack of root penetration (CD) is most often estimated as lack of root penetraion (60%).

Finally the distribution of IIW degrees for the two radiographic interpreters is given in Fig. 2.26.

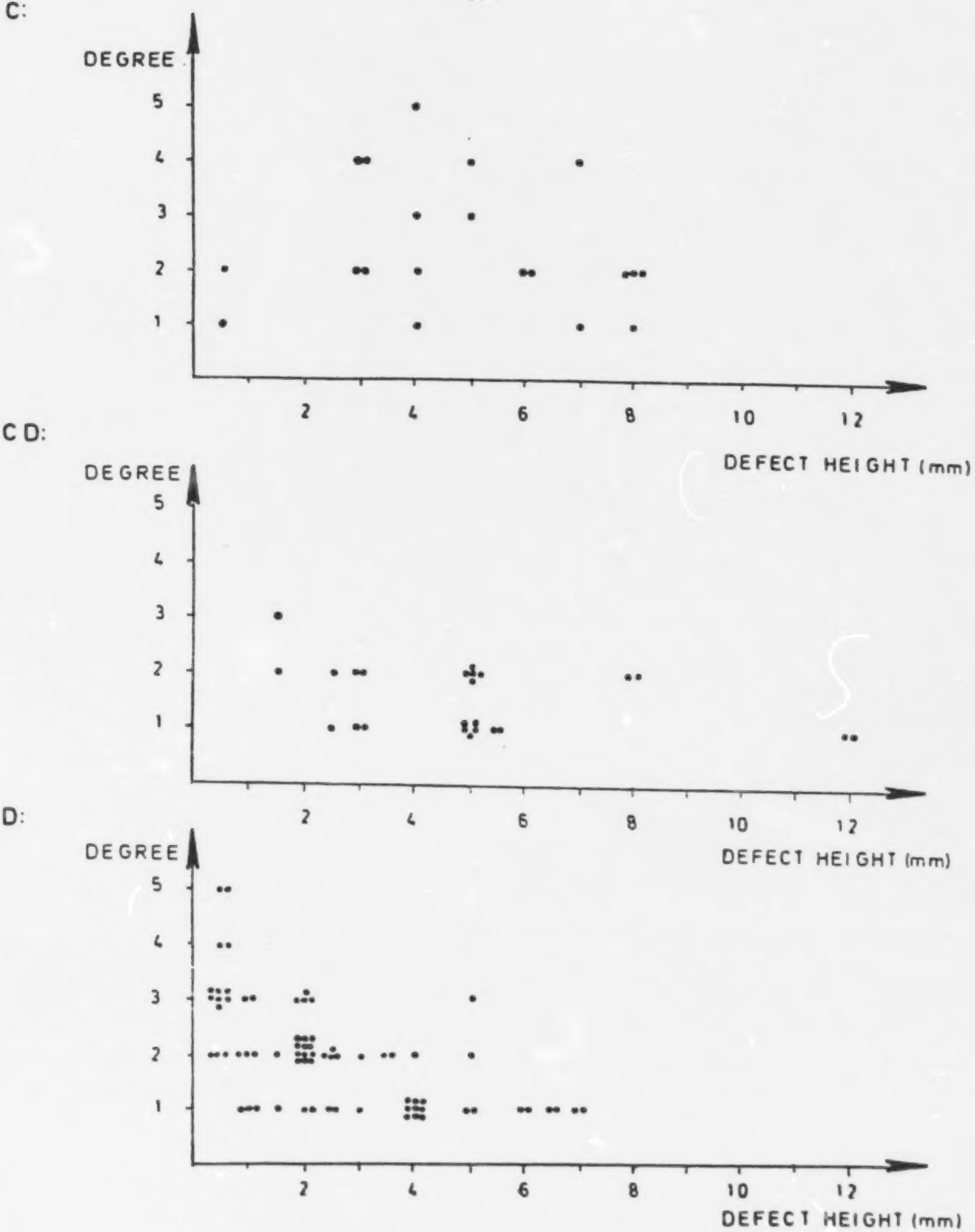


Figure 2.25 Observations of IIW degrees 1-5 versus defect height during radiographic weld examination for defect types lack of fusion (C and CD) and lack of root penetration (D). 2.17

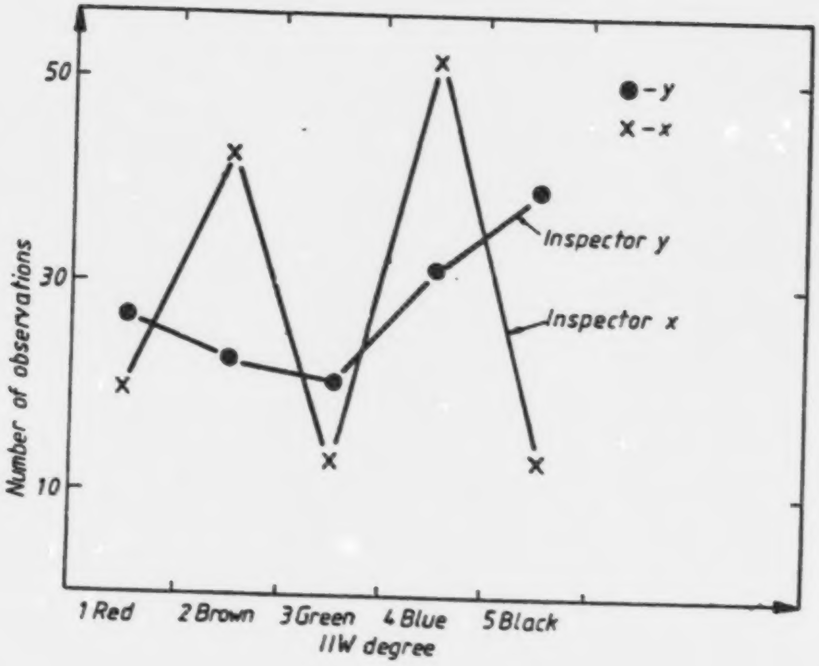


Figure 2.26 Distribution of IIW degrees for two radiographic interpreters 2.17

In most instances, radiographic techniques are employed in dry habitats underwater, however, when RT is performed underwater in wet conditions, it is necessary to account for the sensitivity degradation due to the water layer which must be penetrated. The parameters affecting radiographic sensitivity are listed in Table 2.10.

2.3.6 Remotely Operated Vehicles and Atmospheric Submersibles

2.3.6.1 Manned Submersibles

2.3.6.1.1 Manned Vehicles

One of the main advantages (related to NDE technology) in using manned vehicles is that long umbilicals between measuring device and data-gathering units are eliminated. Hence results are immediate and data interpretation can be performed on-the-spot.

2.3.6.1.2 Atmospheric Diving Suits

The ADS systems are reported to be safe, comfortable, and cost-efficient option to saturation diving and remotely operated vehicles.

2.3.6.2 Remotely Operated Vehicles (ROVs)

There are over 100 different makes of tethered free swimming ROVs on the market, however the reliability of many of these ROVs offshore is questionable. In a recent study[2.18] of the many ROV's available, the following list was prepared indicating ROV components in decreasing failure frequency:

- underwater lights;
- subsea electrical connectors, cables and cable terminations;
- submerged electrical motors;
- vehicle electronics;
- vehicle hydraulics;

TABLE 2.10

RADIOGRAPHIC SENSITIVITY[2.3]

DEFINITION

CONTRAST

GEOMETRY AFFECTED BY	FILM GRAININESS AFFECTED BY	SCATTERING AFFECTED BY	SUBJECT CONTRAST AFFECTED BY	FILM CONTRAST AFFECTED BY
Source size (small source preferred)	Type of film (some films are more grainy than others)	Energy (KEV) of radiation	Thickness differences in specimen (the greater the change in thickness the greater the contrast	Type of film (some films give better contrast than others at a given exposure)
Source-to-film distance (longer distance preferred)	Type of screen (Flourescent screens decrease definition)	Scatter control techniques a) Screens b) Masks c) Collimation d) Plugs e) Filters f) Shot	Density differences in specimen (the greater the change in density the greater the contrast)	Density of film image (the darker the film the greater the contrast)
Specimen-to-film distance (shorter distance preferred)	Radiation energy (KV) used (higher voltages produce more graininess)		Radiation energy (KEV) used (higher energy, less contrast, lower energy, more contrast	
Source offset (source must be on line perpendicular to plane of interest)				
Screen-to-film distance (contact preferred)				
Abruptness of thickness changes in specimen (uncontrollable)				

Moreover, many ROV systems suffer from the following disadvantages in moderate sea states during the launch and retrieval phases:

- pendulum motions of ROV/launcher during hoisting is not sufficiently prevented;
- connecting of launcherless ROVs to the handling gear must normally take place in the surface and hazardously close to the support station;
- strong jerks in the hoisting line often occur when lifting launcherless ROVs out of the waves;
- the umbilical is very vulnerable to entanglement and destruction when separate hoisting line for the ROV/launcher is used;
- lacking heave compensation of the launcher makes ROV homing and clamping to the launcher difficult and hazardous;
- ROV/launcher is insufficiently protected by fenders. Firm mounting of sub systems to the ROV-structure often make them vulnerable to impacts.

In general it has been found that the best results are obtained by using a heavy heave compensated launcher which is handled by a reinforced umbilical and transports the ROV to its operating depth (like the RCV-225).

3. PROSPECTIVE NDE TECHNIQUES FOR OFFSHORE STRUCTURE INSPECTION

There is ongoing research and development in underwater NDE techniques. These developments mainly address the following considerations:

- cost-effectiveness of inspection and maintenance;
- quality of inspection;
- installations in deeper waters.

As an example, summaries of the main NDE research projects currently underway in the UK are given in Appendix B.

The new systems being developed are characterized most of all by the trends towards automation and remote control of equipment, real time signal processing and optimization of NDE efforts. In particular, processing of signals using powerful microprocessors and computers brings new dimensions to both traditional NDE techniques (ultrasonics, radiography, electromagnetic methods, visual methods) and to techniques still under intensive laboratory development (tomography, acoustical holography). Hardware and software are equally important in the computerization of NDE techniques.

Some of these new developments will be discussed in this chapter. It must be pointed out, however, that even though the present state-of-the-art in these techniques may not allow their immediate application to underwater NDE, some of them can come into use in the foreseeable future or their application to fabrication inspection can have a great impact on the quality of the offshore structures and subsequently on the need and frequency of underwater inspection and/or monitoring.

3.1 Inspection Methods

3.1.1 Advanced Ultrasonic Testing

The first ultrasonic testing system was built in 1930. The breakthrough in UT method was the introduction of the pulse-echo technique in 1942. Since then UT instrumentation has undergone considerable development. The most commendable achievement is the ultrasonic diffraction technique measuring the time-of-flight in addition to amplitude recently developed at Harwell. Other developments to be mentioned are defect reconstruction by phased arrays and ultrasonic holography with focussing. Of course automation and computerization play a major role.

3.1.1.1 P-Scan

P-Scan (Projection image Scanning) was developed by the Danish Welding Institute. This technique has been developed for automated ultrasonic weld inspection. Using one or more ultrasonic probes attached to a scanner, all echoes from defects (without a preset detecting level) are permanently recorded and later processing the logged data, a complete, three dimensional location of weld defects is reconstructed.

3.1.1.2 Rotoscan

Rotoscan is a multichannel automated ultrasonic system developed by RTD (Roentgen Technishe Dienst) for inspection of pipeline welds.

3.1.1.3 SUTARS

SUTARS (Search Unit Tracking And Recording System) is a system developed at the Southwest Research Institute, Texas (SWRI).

Scanning with the ultrasonic search unit is done manually. A transducer array is used to locate and automatically record the position of the search unit (including skew). A pulse-echo ultrasonic technique is used to detect, locate and characterize the defects. All indications are also automatically recorded and the operator obtains information in real-time on the coverage of the volume to be inspected. The logged data is then processed and a B- and C-scan of the inspected volume reconstructed.

3.1.1.4 Time-of-Flight Method

The ultrasonic time-of-flight diffraction for detection and sizing of defects in steel sections has been developed at AERE (Atomic Energy Research Establishment), and was developed as an automated inspection procedure[3.1].

This method interprets time delays of the crack edge diffracted signals using the lateral wave (corresponding to the fastest route between the transmitter and the receiver) for timing reference.

After proving capabilities of the method (best sizing accuracy among ultrasonic techniques, Harwell is launching a development program to expand application of the time-of-flight method to complex geometries and should be completed in 1985/86[2.11].

Another sophisticated system using the time-of-flight analysis for NDE of turbine disk rims of a very complex geometry has been developed at the Southwest Research Institute (Texas)[3.2]. The system allows rapid scanning and crack-sizing.

3.1.1.5 TREES

Turbine Rotor Examination/Evaluation System (TREES), developed at the Southwest Research Institute (Texas), is described here to demonstrate NDE technology available in other industries. It uses a focused search unit and high-speed automated data acquisition and processing system. The processed data is then used as input to a program for fracture mechanics failure analysis which predicts the residual lifetime for the rotor in question.

3.1.1.6 Phased Arrays

At the Fraunhofer Institute, Saarbruecken, West Germany a phased array system was developed for defect reconstruction and classification[3.3, 3.4]. The principle of the system incorporates a sound beam which is electronically steered over a specimen sector in a fan-like fashion. Using different probe positions in the array, a defect can be reconstructed and positioned through individual image points.

3.1.1.7 Ultrasonic Holography

Ultrasonic holography is analogous to optical holography with the exception that the object is on focus in a plane. The system uses a matrix of focused ultrasonic transducers which act both as transmitters and receivers. The signal amplitude, time and phase are monitored using an electronic gate. The phased signals are then electronically processed to reconstruct a focused acoustic hologram[3.5].

3.1.2 Enhancement of Electromagnetic Methods

It has been demonstrated that MPI is the most widely used technique for detection of surface breaking cracks in offshore structures. It is felt though that this method can, if further developed, yield much more quantified information about the defect size, character and location. The UK Welding Institute, responding to the needs of various sectors of industry, is launching a project entitled "Optimized Magnetic Particle Inspection Technique for Welded Joints".

Within this project, finite elements will be used to model the magnetic leakage field caused by both geometry and defects of the welded joint. Also, reliability of MPI shall be systematically investigated to account for spurious indications.

At Harwell, a pulsed eddy current method is being developed to give multiple frequency data so that greater accuracy and discrimination can be achieved on crack depths as compared to single frequency systems. Special analogue circuitry shall provide signal processing of digitized eddy current signals.

3.1.3 Computerized Tomography

Computerized tomography, reconstructing cross-sectional images of inspected specimen, was developed and still is mainly used in medicine. Tomography evolved from radiography when exposures of the object were taken from different angular positions. After the reconstruction algorithms were developed[3.6, 3.7], radiographic images were digitized and powerful computers used (e.g. CDC 7600[3.8]) to reconstruct the sectional views (tomograms). Depending on the size and mass of the inspected object, gamma rays from Iridium-192, Cesium-137 or Cobalt-60 isotopes as well as lower energy x-rays or even neutron beams have been used to generate tomographic images.

3.1.4 Enhanced Visual Inspection

3.1.4.1 CARTIS

Computer Aided Real Time Inspection System (CARTIS) has been developed by BIX International Services (UK). The system uses a computer and special software to perform the desired functions such as image enhancement, co-ordinate measurements or automatic component inspections.

To demonstrate the degree of enhancement available, the human eye can define a maximum of 64 shades of gray whereas for a TV camera, each frame of information will consist of a matrix of 512 x 512 pixels and each can have one of 256 gray scales.

3.1.4.2 Optical Holography

A feasibility study on the use of optical holography underwater for inspection and recording has been undertaken at the Gordon Institute of Technology, Aberdeen (UK)[3.9]. It has been concluded that optical holography would be successful underwater under the same visibility conditions as would be necessary to produce good photographs. A holographic image can contain 10^{15} bits of information per square meter compared to 10^{10} bits/m^2 possible by high quality photography. A single hologram could, therefore, provide the same amount of information as several thousand photographs.

The best dynamic stability is achieved by the use of a pulsed laser. The attenuation in light intensity with distance from the source would be greater in the water than on the surface and the maximum scene depths of 1-2 m are feasible with laser energies of 1-10 J.

3.2 Prospective Inspection Equipment

Descriptions of prospective NDE equipment are presented in Appendix A. The equipment described are used in the following techniques:

- advanced ultrasonic testing;
- enhanced electromagnetic methods;
- computerized tomography; and
- enhanced visual inspection.

3.3 Assessment of Prospective NDE Methods

3.3.1 Advanced Ultrasonic Testing

3.3.1.1 P-Scan

P-Scan has been used successfully in VERITAS' Corroscan equipment described in Appendix A.

3.3.1.2 Rotoscan

At present a sub-sea version of Rotoscan is built for a 50m depth. Further development for depths up to 250m is considered. As a part of the work, the problem of long cables using glassfiber optics was dealt with.

To inspect complicated welds in tubular joints, RTD is developing a microprocessor-controlled scanner with up to 6-axes controlled movement.

3.3.1.3 SUTARS

SUTARS was developed to eliminate the main disadvantage with manual ultrasonic testing, i.e. the lack of a permanent record whether the CRT is underwater or the inspector has it available also on the supporting boat. The problem is with ensuring that the whole inspected area is covered, with positioning of the probe and recording manually any above threshold indications of the A-scan.

3.3.1.4 Time-of-Flight Method

For the system developed at the Southwest Research Institute, the time-of-flight method allows extensive cost and time savings over the currently used MPI method because it does not require the costly and time consuming removal of the turbine blades[3.2]. (Refer also to section 3.1.1.4).

3.3.1.5 TREES

Since TREES is still being developed, an assessment is not possible at this time.

3.3.1.6 Phased Arrays

The phased array systems are still in the development and laboratory trial stage.

3.3.1.7 Ultrasonic Holography

Holosonics Inc. (USA) spent several years on development of acoustic holography to meet the objectives of underwater inspection[3.10]. This system can be applied by submersible manipulation systems or manually by divers from a lockout vehicle. The flaws can be viewed in real time by an inspector and permanent records kept on videotape, magnetic tape or hard copy prints. Flaws can be located, magnified for close examination and then reconstructed in three-dimensions by utilizing logged data. However, the present state of development of acoustic holography does not yet allow for its commercial use as an underwater inspection tool.

3.3.2 Enhancement of Electromagnetic Methods

Since new methods and systems being investigated at the UK Welding Institute and at Harwell are still in the development stage, an assessment is not possible at this time.

3.3.3 Computerized Tomography

Despite some encouraging results, tomography is still in the development stage and its present use as an NDE technique is limited to very special cases.

3.3.4 Enhanced Visual Inspection

3.3.4.1 CARTIS

Enhanced systems such as CARTIS have a good potential to be used for inspection of offshore structures either operated mannually be a diver or installed on ROVs.

3.3.4.2 Optical Holography

Optical holography has the potential of being used as a part of future inspection equipment installed on ROVs or being used by a diver from a lock-out vehicle.

4. INSTRUMENTED MONITORING OF OFFSHORE STRUCTURES (IMOS)

4.1 General

Present methods of underwater inspection are both risky and expensive in addition to being highly dependent on weather conditions. These methods are applied locally and there is no guarantee that a significant defect will be found. It is not envisaged at present that monitoring systems would substitute NDE, rather complement it. One great advantage of continuous monitoring, as compared to traditional periodic inspection, is that monitoring would not interfere to any significant degree with normal operations on the platform. Recently conducted research and development in instrumented monitoring techniques shows that major contribution to the safety and economy of offshore structures can be made by implementation of such a system. For structures in water depth range of 70-150 m the instrumentation will be used together with diver inspection. For structures in deeper waters, ROVs would provide the complementary inspection.

In view of its significant potential impact on offshore inspection, a discussion on IMOS is presented in this chapter.

4.2 Objectives of IMOS

Monitoring systems can be divided in two basic categories:

1. Monitoring systems which would give warning of catastrophic failures. The objective of these systems would be to prevent loss of life by providing advanced warning for evacuation of the platform.

2. Monitoring systems which would give early warning of local failure taking place before the structural integrity of the whole structure is threatened. This would allow repairs to be undertaken.

The latter systems, which can significantly contribute to the prevention of major structural failure will prove most valuable, particularly when deployed in conjunction with NDE.

Such IMOS systems must meet the following objectives:

- detect significant changes in structural response and environment;
- collect, store and evaluate data from the observations of response and environment;
- interface with relevant structural consequence analysis;
- assess the damage in terms of: need for repair, time limit for the repair, need for further inspection, possible limitations in the operations of the structure before, during and maybe also after the repair.

4.3 Description of IMOS

A typical IMOS system (Fig. 4.1) comprises the following subsystems:

- detection and data acquisition subsystem;
- analysis subsystem;
- communication subsystem;
- reporting subsystem.

IMOS further interacts with other subsystems such as DFI, structural reanalysis, inspection, maintenance, etc. In other words, the system must be compatible with an overall design, inservice inspection and maintenance strategy suitable both for the operators and the authorities.

The detection subsystem monitors both the structure and its environment and transmits the data to the data acquisition unit for checking and formatting. The formatted data is then transmitted to the analysis subsystem which performs the relevant analysis (structural reanalysis). The reporting subsystem then provides the competent personnel with the results of the analysis as the basis for decision making. A schematic flow chart presenting various aspects to be considered when designing an IMOS system is shown in Fig. 4.2.

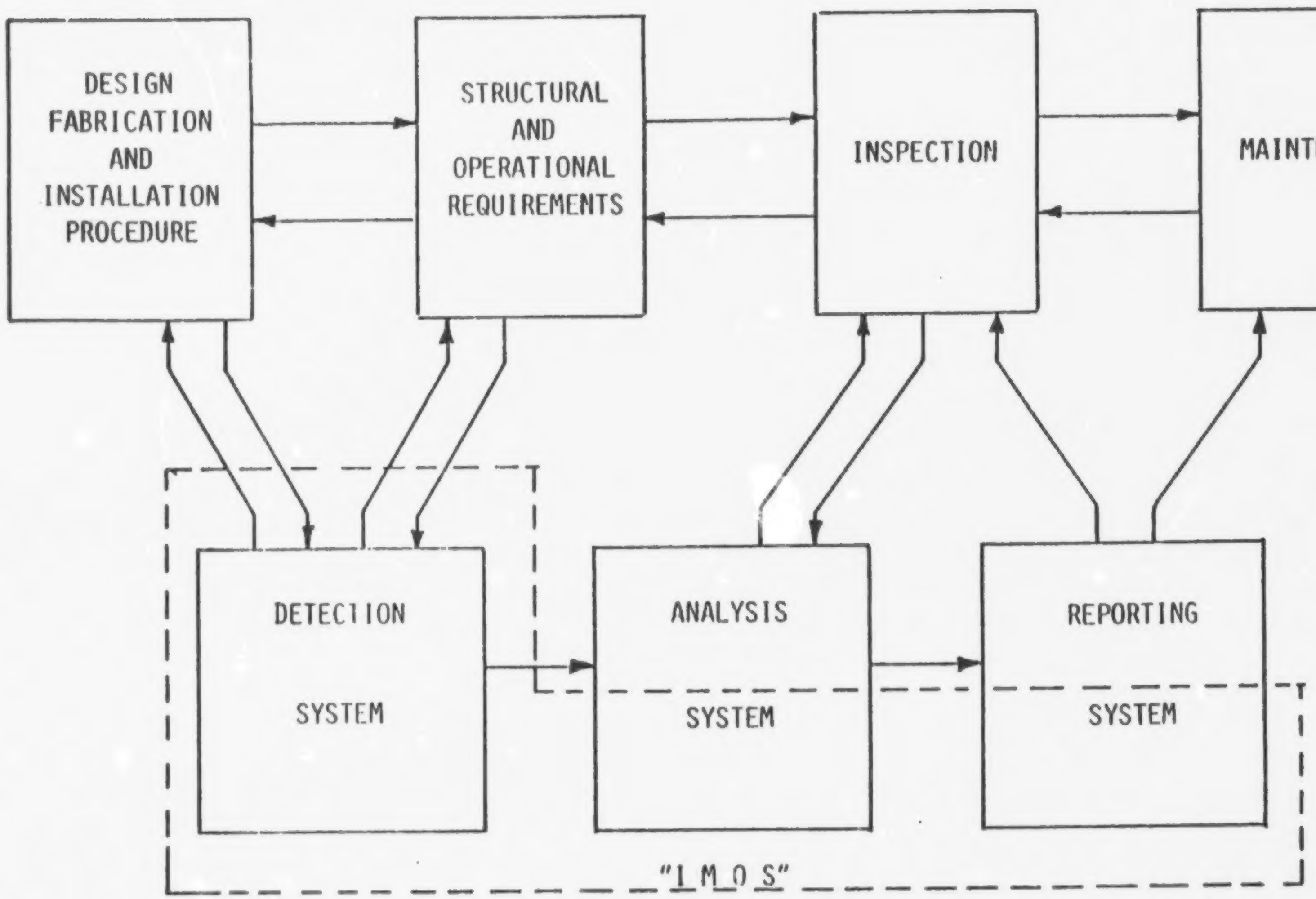

DESIGN FABRICATION AND INSTALLATION PROCEDURE
STRUCTURAL AND OPERATIONAL REQUIREMENTS
INSPECTION
MAINTENANCE
DETECTION SYSTEM
ANALYSIS SYSTEM
REPORTING SYSTEM
"I M O S"

Figure 4.1 Relation of IMOS to Offshore Surveillance System [4.8]

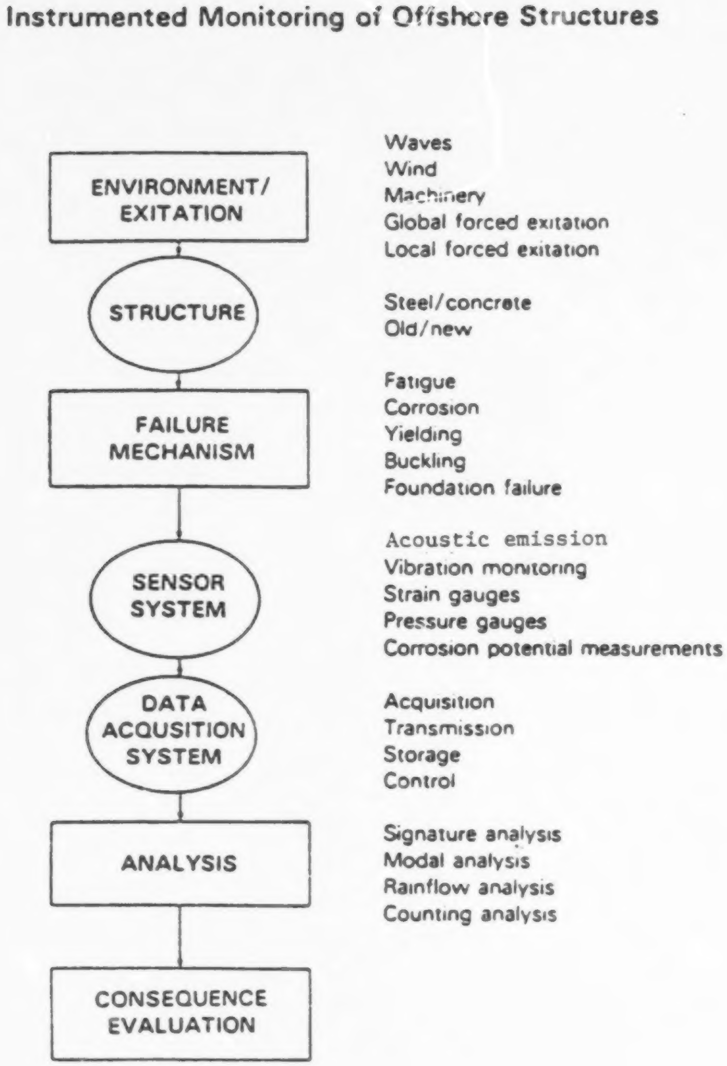

Instrumented Monitoring of Offshore Structures
ENVIRONMENT/ EXITATION
Waves
Wind
Machinery
Global forced exitation
Local forced exitation
STRUCTURE
Steel/concrete
Old/new
FAILURE MECHANISM
Fatigue
Corrosion
Yielding
Buckling
Foundation failure
SENSOR SYSTEM
Acoustic emission
Vibration monitoring
Strain gauges
Pressure gauges
Corrosion potential measurements
DATA ACQUSITION SYSTEM
Acquisition
Transmission
Storage
Control
ANALYSIS
Signature analysis
Modal analysis
Rainflow analysis
Counting analysis
CONSEQUENCE EVALUATION

Figure 4.2 Items to Consider when Designing a System for Instrumented Monitoring [4.8]

In the following, only the first part of IMOS, the detection subsystem will be discussed. Only those detection techniques will be described which are considered as potentially attractive to be used with IMOS systems.

4.4 Detection Methods

There are a large number of methods available which are suitable for detection of structural damage[4.1]. These methods can be divided into two groups:

- methods for local monitoring;
- methods for global monitoring.

Some local monitoring methods can be used to cover the whole structure.

In selecting a detection method, both detection capability and cost of implementation and operation have to be considered. Also reliability of the system in long term operation is an important factor. The system has to be rugged to continue operating under storm conditions when structural failure would be most likely to occur. A different approach has to be taken in designing an IMOS system for a new structure at the fabrication and installation stage from implementing a monitoring system on offshore structures already in operation. The detection techniques shall be reviewed with preference to monitoring steel structures.

The monitoring approach assumes a fail-safe design of the structure with such degree of redundancy that adequate warning of structural response changes can be given before the loss of structural integrity of the whole structure is imminent. Such early warning would allow repairs without large economic losses.

4.4.1 Vibration Methods

The techniques can be divided into two major groups:

- Passive. This method utilizes vibrations present in the structure from natural sources such as waves, machinery, equipment, etc.
- Active. This method needs an excitation source such as constant amplitude sine sweep (rotating weight or electromagnetic excitation), impulse source using mechanical hammer or small explosions, or random electromechanical excitation with a defined band width.

The active vibration method has the disadvantage of the nuisance and disturbance to the platform personnel caused by the vibrations introduced in the structure.

The principle of vibration methods lies in monitoring and evaluating dynamic response of the structure to external excitation. A regular pattern of response is processed by dedicated computer and changes, in natural frequencies are indicative of structural changes. The change in natural frequencies can be caused by such events as missing member, flooded member, change in foundation, marine fouling or redistribution of live loads on the platform. Usually spectrum analysis of acceleration records is used to determine two flexual frequencies, in two vertical perpendicular planes, and a torsional mode. For example, after a vessel collision with the Buzzards Bay Entrance Tower, the damage underwater was evaluated using vibration technique[4.2]. The tower was analysed using MITs ICES-STRUDL II finite-element program. Table 4.1 shows the change in fundamental flexural natural frequencies caused by damage in various parts of the tower, Fig. 4.3.

Analysis of the Buzzards Bay Tower led to the conclusion that structural damage causing change in natural frequencies of 2% or greater can be detected[4.2]. The most important sources of uncertainty are the long-term changes in mass (marine fouling, flooded members), changes in supporting bottom conditions, and particularly changes in the deck live loads (sloshing liquids in tanks, etc.).

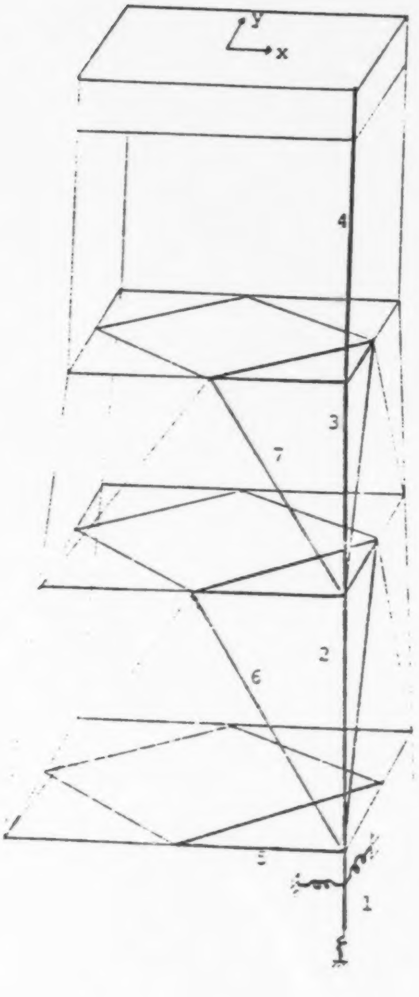


Figure 4.3 Schematic of the Buzzards Bay Tower [4.2]

TABLE 4.1

FUNDAMENTAL FREQUENCY REDUCTION DUE TO DAMAGE[4.2]

Damaged Member		Percent Reduction in Frequency	
		Δf_x	Δf_y
1.	Piling	17.14	17.14
2.	Lower Leg	11.15	11.15
3.	Middle Leg	5.92	5.92
4.	Upper Leg	8.80	8.80
5.	Minor Horizontal	0.12	0.0
6.	Lower K Brace	6.10	0.17
7.	Upper K Brace	7.18	0.0

It depends very much on the computer model and possibly on the capability to monitor and analyse higher freqencies to separate structural damage from these other causes of change in natural frequencies. Even the type of failure may be deduced from relative shifts in frequency.

4.4.2 Acoustic Emission (AE)

When stressed, many solid materials (metals, wood, fiberglass, etc.) generate transient elastic waves as a result of rapidly released energy. Such (acoustic) emissions can be generated by several phenomena, such as local plastic deformation in the vicinity of stress risers, crack initiation, and crack growth or phase transformations.

Piezoelectric transducers can be used to monitor these acoustic emissions and using computerized signal processing with necessary amplification and noise filtering, typical defect signatures can be obtained[4.3]. The frequency range of these acoustic emissions lies generally between 100 kHz and 1 MHz.

Thus by measuring acoustic emissions, it is possible to monitor crack propagation and give warning well in advance of failure and loss of structural integrity. On large structures, a triangulation technique can be used to locate the source of the monitored emissions.

The acoustic emission technique has been used very sucessfully as an NDE tool for inspection of pressure vessels, particularly nuclear[4.4].

AE has potential to be used as a monitoring technique for offshore structures[4.1, 4.5]. It would be best used locally to monitor selected "hot spots" with limited number of transducers.

AE is attractive as a passive system with a limited number of transducers to cover a large area (50 m between transducers seems to be realistic). The method is limited to steels having high signal to noise ratio. Some steel types used offshore (with high fracture toughness) are claimed to have low levels of emissions during fatigue. The signal processing is an important part of the system and must be capable of eliminating extraneous noises.

A significant disadvantage of this technique is its inability to provide reproducible results because after the defect gets "accustomed" to the current stress level, it becomes dormant until reactivated by an increased stress level. The defects would be especially active when high environmental loads (high strain energy) would be acting on the structure during storms when also structural failure would be most probable.

It is generally believed that AE technique has the potential to identify and size the defects, as well as locating them.

4.4.3 Acoustic Pulsing

The U.K. Welding Institute recently patented a novel technique (acoustic pulsing) which can be used for monitoring structural integrity. It is claimed that this technique would overcome some difficulties of both vibration and acoustic emission techniques[4.6].

The principle of acoustic pulsing is to inject a constant acoustic pulse, preferably of ultrasonic frequency, into the structure from one of a network of widely spaced (tens of meters) transducers fixed to the structure. The signal is modified when passing structural members between the input transducer and receiving transducer. A signature of any structural change can be evaluated by comparison with previous records. The technique should be capable of:

- detection of the extension of the flaw;
- location of the region of flaw growth;
- estimating the amount of flaw growth.

This method can be used for overall scanning of the structure.

With only 0.1 W of electrical drive, transmission over 9m has been achieved with a 400 kHz signal. A particular advantage of the method is that pulsing can be repeated during a given monitoring cycle to check the validity of the recorded signal. Inter-transducer distances can be up to an order of magnitude greater for acoustic pulsing than for AE.

The potential of acoustic pulsing has yet to be proven through offshore trials.

4.4.4 Ultrasonic Technique

Principle of ultrasonic technique was described in previous sections. As far as structural monitoring is concerned, ultrasonic scanning may be limited to a selection of critical welds. If three transducers would be used to monitor one circumferential weld, any crack so found could extend around some 30% before being discovered. One ultrasonic probe operating at 1 MHz frequency can scan only a limited area of no more than 4 cm^2. A complete monitoring of a relatively small tubular member may need 100 ultrasonic probes for full monitoring which would be uneconomical.

It seems that ultrasonics would be limited to characterization and sizing of defects located by other methods or to monitoring of a small number of highly stressed "hot spots" in the structure.

4.4.5 Flooded Member Detection

The majority of offshore structures are built by welding together hollow tubular members. Integrity of the members can be monitored by checking on their lead tightness. Various witness techniques can be used to detect flooded members[4.1]. Also ultrasonics can be adapted easily to monitor flooded members taking advantage of different acoustic properties of water and air[4.7]. Pressured air would provide other means for checking the water tightness.

4.4.6 Strain Gauges

Strain gauges are widely used mainly for experimental confirmation of design loads measured on structures during operation. Strain gauge data has been obtained from several offshore structures to check strains calculated from finite element analysis under assumed loading conditions. The data collected and recorded from strain gauge measurement reflects the loading history and provides a valuable input for fatigue life calculations.

A promising development in strain gauge instrumentation is the AILTECH weldable strain gauge. Rugged construction and positive attachment together with waterproof and pre-tested cables makes these gauges suitable for strain monitoring of offshore structures. The AILTECH strain gauges can be used for a wide range of static and dynamic measurements.

A great disadvantage is the poor strain gauge reliability particularly underwater. A failure rate up to 40% in a 4-year period indicates a limited application of this technique for long-term (more than 20 years) monitoring of offshore structures[4.1].

4.4.7 Attitude Measurement

A measurement of deviation of offshore structure attitude from its initial value can be monitored. Also the rate of change in attitude of the structure can be measured. It seems that this technique, due to lack of sensitivity, could be used for global monitoring of the overall structural integrity giving a warning of pending catastrophic failure to prevent the loss of the platform crew.

4.4.8 Other Techniques

Some other techniques such as magnetic methods, electric current testing, microwave testing, thermal and infrared technique, radiographic technique are believed to have little potential as a part of IMOS[4.1]. Underwater enhanced TV viewing (including colour and stereo technique) and sonar technique (Sound Navigation and Ranging) have potential to be developed in connection with inspection done by ROV's and manned or unmanned submersibles.

4.5 Example of IMOS

Figure 4.4 shows an example of IMOS based on three monitoring techniques[4.8]:

- strain gauge measurement at selected locations for fatigue monitoring;
- integrity monitoring (global) using vibration technique;
- local monitoring of "hot spots" using acoustic emission.

The instrumentation will be based on special data acquisition modules, placed on the structure near the sensors, using cableless transfer of data to the surface logging and preprocessing units. From here, the data will be transferred to an onshore data analysis centre for further processing and analysis. This system would avoid the use of underwater signal and power cables as these are very vulnerable to damage in the harsh marine environment. The modules will be placed in watertight cabinets of glassfibre reinforced polyurethane with power supply from lithium batteries with an expected life of 5 to 10 years. The hydroacoustic transmission system is capable of transferring data at a rate up to 2 kilobaud within a distance of 2-3 km. This IMOS system has been developed by DnV for Norsk Agip A/S.

4.6 Equipment for IMOS

4.6.1 Vibration Detection Equipment

Equipment using an "active" approach to vibration detection is produced by Syminex located in France. The Syminex Vibrodetector gives a shock to bracings in the steel jacket via a pneumatic impactor and measures the resulting vibrations. The signals (excitation and response/force and acceleration) are then transmitted by a waterproof armoured cable to the data acquisition equipment located on the platform deck where they are filtered, digitized and recorded on magnetic tape. During measurements, the recorded signals can be treated on site by the data acquisition mini-computer. Readings from subsequent inspections are then compared to readings obtained from the previous inspection(s) which have been stored in the memory of the Fourier analyzer, thereby indicating the existence of cracks. This allows the results of each inspection to be known immediately on site.

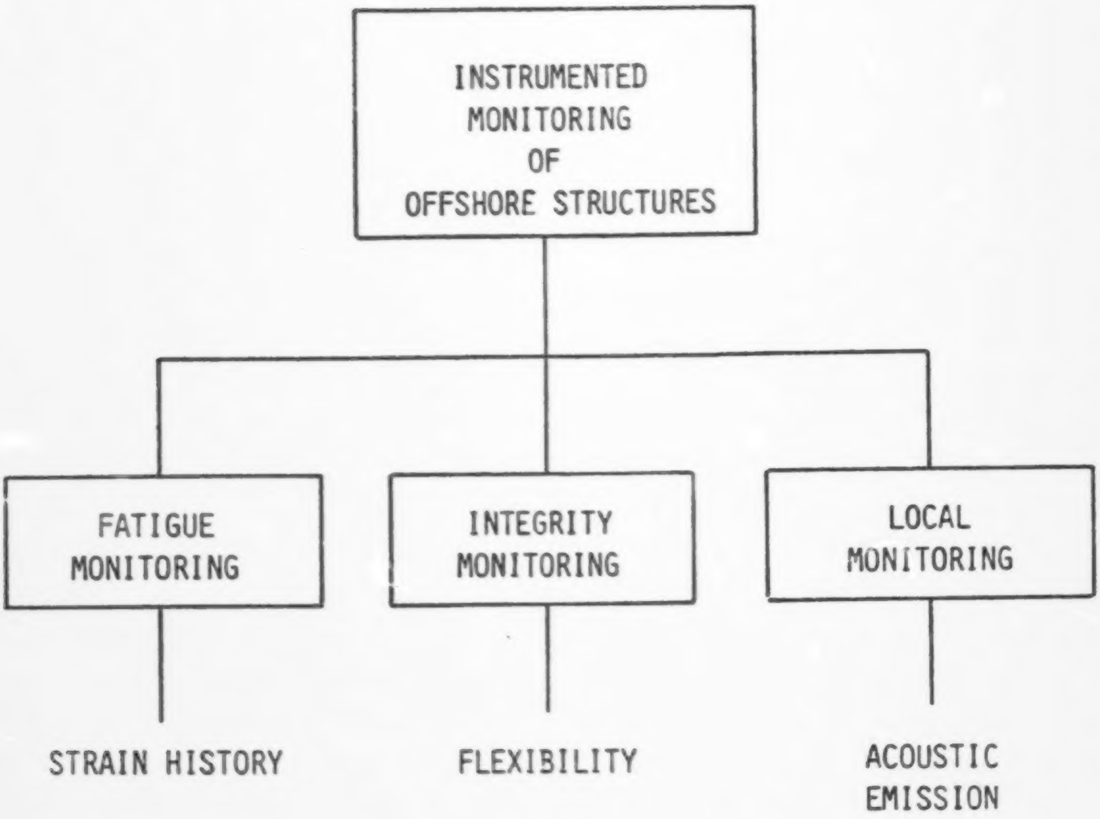

INSTRUMENTED MONITORING OF OFFSHORE STRUCTURES
FATIGUE MONITORING
INTEGRITY MONITORING
LOCAL MONITORING
STRAIN HISTORY
FLEXIBILITY
ACOUSTIC EMISSION

Figure 4.4 Example of IMOS System 4.8

With the present Vibrodetection equipment (operational to a depth of about 100m) all flooded bracings can be detected. In addition, through cracks of the leg by punching (without flooding of the bracing) can be detected to 75% (ratio of external crack length to member circumference) for K-nodes and 50% for Z-nodes. An inspection using Vibrodetection does not require a cleaning procedure for bracings.

The cost to perform an inspection using Vibrodetection depends largely on the configuration of each jacket to be examined. A typical North Sea jacket with testing of 150 bracings (at about 3 bracings per hour) can cost about US $45,000 (not including travel and transportation expenses).

Tests using Vibrodetection equipment have been carried out since 1980 in the North Sea, the Persian Gulf and in Indonesia with performance of the technique reported to be satisfactory. As an example, short term repeatability (a few days) was tested on the L7C Platform in the North Sea in September 1981. Differences between successive measurements were smaller than the resolution of the measurements: i.e. less than 0.2%.

The same platform was also the object of long term stability tests. The first test, which consisted in taking reference measurements on several bracings, was carried out in September 1981. The second test took place in April 1982. This consisted of taking the same measurements and comparing them to their reference values. The variations observed were less than 2%. After further processing, it appeared that most of these variations were due to lack of frequency resolution rather than actual change in the mechanical properties of the bracings.

4.6.2 AE System Equipment

Various AE systems are currently available. One of these is the DART-32 system which features the DART (Data Acquisition in Real Time) system together with DAM (DART Activity Monitor) and CAM (Computer Analysis Monitor) of the Dunegan Corporation. The DART-32 system provides a real time display of acoustically active sources and their relative severity. The DART-32 accepts inputs from up to 32 sensors, measures relative arrival times, calculates source coordinates, and displays source information in real time on a storage display scope (CRT). In addition, the DART provides a complete event description including event amplitude, risetime, number of ringdown counts and pulse duration. Pertinent event information is reported by a 150 character-per-second teleprinter and recorded on floppy disk for future use. The DART-32 CRT provides an instantaneous display of the location of each AE event in relation to the position of the sensors (array) involved. In addition, the event attributes of amplitude, risetime, counts and pulse duration can be used in real time (or post-test) to provide plots of time history, distribution functions, and correlations with external parameters (e.g. pressure) or one of the other attributes.

The DART can be used as a stand-alone system for data acquisition, and in conjunction with a Tanberg recorder could be used to obtain information for later analysis with the CAM. The DAM can be utilized during data acquisition of the DART to monitor activity and provide limited analysis and plots of activity as a function of other analog parameters.

The DART family system prices range from US $70,000 to US $115,000 depending on options.

The Dunegan 8000 is a self-contained, single portable unit providing a maximum of 8 channels of sensor signals. The system incorporates signal processing, computer analysis, applications-oriented software, mass storage, audio monitor, and a split-screen display.

The Dunegan 8000 provide simultaneous location and monitoring of event activity and the analysis of event characteristics in real time. Analysis graphs which are available to the user include:

- total counts vs time;
- count rate vs time;
- count rate histogram;
- total count histogram;

- total event histogram;
- amplitude distribution;
- cumulative amplitude distribution;
- current event average amplitude;
- current average signal level histogram;
- parameter vs time.

Prices of the 8000 series range from US $20,000 for a minimum 2-channel system to US $55,000 for an 8-channel system will all options.

Both Dunegan systems can be used in conjunction with the Dunegan S9206 Underwater Acoustic Emission Sensors. The sensor incorporates a built-in preamplifier along with a highly sensitive element of piezoelectric material and can be used to depths of about 1000 feet.

Another acoustic emission crack monitoring (AECM) system has been developed by Syminex[4.9]. The system is built around the DART unit provided by Dunegan and an HP 1000L computer. With this system, analysis of data is not given in real time, rather, acquired data are recorded on a magnetic tape which is subsequently processed and interpreted onshore. Information obtainable from the tape includes location maps of acoustic sources, statistical data (number of events, histrograms) and conclusions on the growth of a crack.

4.6.3 Flooded Member Detection Equipment

Syminex together with Campagnie Francaise des Petroles developed Pressio-Detection for a continuous survey of all bracings of a steel jacket, by measuring the pressure in braces, which were initially pressurized, and transmitting the date to the deck by acoustic transmission.

The underwater equipment consists of a differential pressure sensor and an acoustic emitter (transducer) on each member. Therefore no cables are required. The deck equipment is built around a Hewlett Packard HP85 computer and an acoustic receiver. Values of the pressure are displayed every week on a printer. If a defect (through-thickness crack) is detected, results are displayed every four hours and alarms (warning lights) are set off.

Two offshore trials with this monitoring system yielded very good results and the system is going to be installed on a platform in the Indonesion field. There are no depth limitations. Commercial cost is as yet unavailable.

5. CONCLUDING REMARKS AND RECOMMENDATIONS

The non-destructive evaluation of an offshore structure is performed to assess the fitness of the structure to continue fulfilling its functions safely. The evaluation is commonly based on the results of inspection which is carried out periodically or in response to damages sustained by the structure. It should be stressed that the timely detection and repair of structural defects and damage can significantly contribute to the prevention of major offshore catastrophies or the disruption of production.

Experience shows that the main defects encountered in inspection are cracks and corrosion, and that a type III inspection is most critical for meeting the principal objectives of non-destructive evaluation. Methods that are currently used for type III are:

- close visual inspection by divers;
- radiography (gamma-ray, x-ray);
- ultrasonic testing;
- magnetic particle inspection.

NDE methods based on ultrasonics have been found in general to be suitable for underwater use and recommended for the examinations of internal defects and wall-thickness measurements where the velocity of sound propagation through the material under examination is known. Various methods based on the principles of electromagnetism have also proved useful in the underwater detection of surface defects.

Our survey shows that the common practice in equipment development is the modification of what has been successfully used above water to make it operational underwater.

The survey reported in this study indicates that some operators claim that few defects have actually been detected in planned type III inspection. Undoubtedly the reliability and quality of offshore inspection should be improved. The standards of documentation of inspection reports and repeatability of observations have been identified to require upgrading. Aids for visual inspection should also be improved.

It is evident from the survey of NDE organizations that considerable expertise in NDE and offshore inspection has been accumulated in major offshore areas such as the North Sea. There is also NDE expertise in Canada which forms a base for both the transfer of the latest NDE technology and the development of new techniques and equipment.

The review of the NDE techniques under development indicates that the emphasis will increasingly be on automation and the remote control of equipment, as well as on real time signal processing and the optimization of the operations involved in offshore NDE. The development of such new techniques as ultrasonic holography and computerized tomography are still in the experimental stage and cannot therefore be assessed on the basis of performance in real offshore situations. However, as discussed in Section 3 encouraging results have been obtained during the development of these and other novel techniques.

The instrumented monitoring of offshore structures (IMOS) has been discussed in section 4 for it closely relates to and complements NDE. One significant advantage of continuous monitoring made possible by IMOS, in contradistinction to periodic inspection, is that monitoring would not interfere, at least to any significant degree, with the normal operations on the platform. Furthermore the information obtained from IMOS will provide a most valuable feed-back to test design assumptions. For structures in water depth range of 70-150m IMOS can complement diver inspection, whereas in deeper waters it can be used with ROVs.

On the basis of the present study the following recommendations are proposed for the consideration of CANMET:

- the in-service inspection should be an integral part of the overall safety assessment of offshore installations;

- the criteria for periodic type III inspection should be critically reviewed and rationalized;
- the reliability and feasibility of techniques not regularily applied in underwater inspection such as acoustic emission testing, ultrasonic-time-of-flight and techniques based on electromagnetic changes should be assessed;
- rigorous procedures for documentation and independent verification of recorded observations should be established;
- in view of the harsh environment in which inspection data is acquired, and several examples of unsatisfactory reliability of underwater defect detection, emphasis should be put on the development of semiautomatic and fully automatic underwater NDE systems; this should include further improvements of manipulator arms for ROVs;
- the rough operational conditions offshore and the rather frequently occurring delays reported due to equipment breakdown focus on the need for procedures which would ensure thorough checking of equipment prior to use, and stricter equipment specifications aiming at improved reliability;
- high quality still photos and video recording are extremely valuable and underwater CCTV Systems using high-resolution cameras with magnifying options should be further developed;
- procurement of equipment for laboratory investigation is not deemed to be a priority in Canada. In view of the NDE hardware currently in use, or being developed, it would seem that further investment at this point in time is not warranted;
- provision of incentives for implementation of training programs, perhaps through joint-ventures between Canadian and foreign companies, should be considered. Such joint-ventures that effectively transfer the technology to Canada on a permanent basis should be encouraged and supported. The government can be an effective instrument is implementing training programs;
- monitoring of on-going research and possibly buying into research and development projects that are being currently carried out are considered to be potentially valuable. Canada should of course participate in the development of advanced methods and equipment for NDE equipment, once the most promising ones have been identified in the light of the findings of current research and development work.

6. ACKNOWLEDGMENT

This work was performed for the Physical Metallurgy Research Laboratories, CANMET, Energy Mines and Resources Canada under Supply and Services Canada Contract no. OSQ83-00035. The authors acknowledge the support received from Dr. D. Mak, PMRL, in the scientific administration of the contract.

7. DISCLAIMER

Unless referenced, any data presented, opinions, findings, conclusions, or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of CANMET.

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8. REFERENCES AND BIBLIOGRAPHIES

8.1 References

1.1 Bosselar, H.; "The State of the Art of Underwater Inspection". European Petroleum Conference, 1982, Paper No. 334.

1.2 U.K. Statutory Instrument No. 289, Offshore Installations (Construction and Survey). Regulations 1974.

1.3 Offshore Installations: Guidance on the Design and Construction. U.K. Department of Energy, 1977.

1.4 Guidelines for the Inspection of Primary and Secondary Structures of Production and Shipment Installations and Underwater Pipeline Systems. Norwegian Petroleum Directorate, 1977.

1.5 Enforcement of Article 34 of the Mining Regulations for the Continental Shelf and Article 36d of Mining Regulations 1964 for fixed Installations. Dutch Mining Directorate, 1978.

1.6 Newfoundland Regulation 183/82. The Offshore Installations (Design, Construction and Survey) Regulations, 1982.

2.1 Lumb, R.F. and Winship, P.; "Magnetic Particle Crack Detection". Part 1, Metal Construction, 1977, 9, 7, pp. 293-296. Part 2, Metal Construction, 1977, 9, 8, pp. 331-334.

2.2 Auchterlounie, A.J.; "Magnetic Particle Inspection Underwater - The True Potential". Journal of the Society for Underwater Technology, 8, 3, 1982, pp. 17-20.

2.3 "Non-Destructive Testing, Principles and Limitations". Veritas Training Center, January 1983.

2.4 Walther, K.G.; "The Magfoil Method". Materials Evaluation, April 1983.

2.5 Stumm, W.; "Magnetographic Weld Inspection System for Underwater Installations". Materials Evaluation, April 1983.

2.6 Zeller, R.; "Risstiefenmessung nach dem Potentialsondenverfahren mit Wechselstrom". Materialpruef, 23, 3, 1981.

2.7 Haugen, R. and Rangnes, E.; "A New Instrumentation for Fatigue Crack Depth Measurement with A.C. Potential Drop Technique". Second European Conference on Non-Destructive Testing, Wien, 1981, Veritas Paper No. 81 P050.

2.8 Moncaster, M.B.; "Underwater Inspection of Welds - An Assessment of Some Techniques and Their Reliability". Journal of the Society for Underwater Technology, 8, 3, 1982, pp. 7-12.

2.9 Sletten, R.; "Prerequisites of Effective Inspection in Light of Recent Experiences from the North Sea". Veritas Paper No. 81 P004, January 1981.

2.10 Dalberg, P., Haugen, R. and Myrhaug, O.; "Crack Depth Determination - The AC - Potential Drop Technique". Veritas Technical Report: 81-1079, November 1981.

2.11 Mudge, P.J. and Williams, S.; "Performance of Ultrasonic Nondestructive Methods for Defect Assessment in Relation to Fracture Mechanics Requirements". Fitness for Purpose Validation of Welded Constructions, London, 1981, Paper No. 44.

2.12 Foerli, O. and Pettersen, B.; "Reliability of Ultrasonic and Radiographic Testing". Fitness for Purpose Validation of Welded Constructions, London, 1981, Paper No. 27.

2.13 Singh, A., McClintock, R.; "Computer-Controlled System for Nondestructive Thickness Measurement of Corroded Steel Structures". Journal of Energy Resources Technology, Vol. 105, December 1983.

2.14 Hoegmoen, K. and Veierland, S.E.; "Corroscan - An Automated Ultrasonic Equipment for Corrosion Inspection". International Conference on Pipeline Inspection, June 1983, Edmonton, Canada.

2.15 Dalgliesh, E.H., Casswell, P.H. and Poole, M.J.; "The Ultrasonic Torch - A Novel Device for Monitoring Steel Structures Underwater". Offshore Technology Conference, 1982, Paper No. 4362.

2.16 Foerli, O., Hansen, B., Sanberg, S., and Aastroem, T.; "A Comparison of Radiographic and Ultrasonic NDE, Pilot Study of a Statistical Model for Evaluation of Examination Performance". The Danish Welding Institute, Nordtest Project 72-76, March 1978.

2.17 Foerli, O.; "Comparison of Radiography and Ultrasonic Testing". Second Nordiske NDT Symposium, Copenhagen, May 1979.

2.18 Kristiansen, O. and Sletter, G.I.; "Diverless Underwater Inspection Program (DUIP)". Remotely Operated Vehicle Conference 1983, California.

3.1 Hawker, B.M.; "The Automation of Inspection of Thick Steel Sections Using the Ultrasonic 'Time-of-Flight' Technique". OECD/IAEA Specialist Meeting on Defect Detection and Sizing, Ispra, Italy, May 1983.

3.2 Singh, G.P., Cervantes, R.A., and Spinks, R.L.; "Ultrasonic NDE Technique for the Examination of Low-pressure Turbine Disk Rims". Materials Evaluation, Vol. 41, December 1983.

3.3 Gebhardt, W., Bonitz, F. and Woll, H.; "Defect Reconstruction and Classification by Phased Arrays". Materials Evaluation, 40, 1, 1982.

3.4 Hoeller, P., et al; "Non-Destructive Ultrasonic Techniques for Classification and Reconstruction of Defects". Fraunhofer-Institut fuer zerstoerungsfreie Pruefverfahren.

3.5 Holographic Non-destructive Testing. Edited by R.K. Erf, Academic Press, New York, 1974.

3.6 Smith, K.T., Solmon, D.C. and Wagner, S.L.; "Practical and Mathematical Aspects of the Problem of Reconstructing Objects from Radiographs". Bulletin of American Mathematical Society, 23, 6, 1977.

3.7 Minerbo, G.; "MENT: A Maximum Entropy Algorithm for Reconstructing a Source from Projection Data". Computer Graphics Image Processing, 10, 1, 1979.

3.8 Kruger, R.P. and London, J.R.; "The Industrial Use of Filtered Back Projection and Maximum Entropy Reconstruction Algorithms". Materials Evaluation, 40, 12, 1982.

3.9 Watson, J.; "Holography - Can it be Used Underwater?". Journal of the Society for Underwater Technology, Winter 1981.

3.10 Stankoff, A.G. and Collins, D.H.; "Application of Acoustical Holography to the Inspection of Offshore Platforms". Offshore Technology Conference, 1978, Paper No. 3332.

4.1 Silk, M.G., et al.; "The Continuous Monitoring of Fixed Offshore Platforms for Structural Failure". A Review and Assessment of Techniques. AERE, HARWELL, 1975, R8055.

4.2 Vandiver, J.K.; "Structural Damage Detection by Measurement of Dynamic Response". SNAME Paper T4-3, 1977.

4.3 Lenain, J.C.; "General Principles of Acoustic Emission". Materials Evaluation, 39, 11, 1981.

4.4 Scruby, C.B. and Wadley, H.N.G.; "An Assessment of Acoustic Emission for Nuclear Pressure Vessel Monitoring". Progress in Nuclear Energy, 11, 3, 1983.

4.5 Dunegan, H.L.; "Acoustic Emmission - New Inspection Technique". Offshore Technology Conference, 1977, Paper No. 2851.

4.6 Bartle, P.M.; "Acoustic Pulsing - A Technique for Remote Defect Monitoring". The Welding Institute Research Bulletin, September 1983.

4.7 Brown, D. and Benett, A.; "NDT Techniques Often Unreliable". Offshore Engineer, May 1981.

4.8 Liland, H. and Flogeland, S.; "IMOS - Instrumented Monitoring of Offshore Structures". Offshore Goeteborg, 1983.

4.9 Lepert, P.; "Acoustic Emission Crack Monitoring System; General Presentation". Societe Syminex.

8.2 Det norske Veritas Bibliography

- Underwater Technology, Veritas' Research and Development Projects for 1984.

- Karlsen, F.; "Codes and Standards NDT - Acceptance Criteria". Veritas' course on Field Inspection, Lecture No. 48.

- Sletten, R.; "Underwater Inspection, Maintenance and Repair on Offshore Structures and Pipelines - Technical Aspects". IOR General Meeting, Vlaardingen, January 1978, Paper No. 78-0022.

- Sletten, R. and Eriksen, H.; "Improving the Efficiency of Inspection and Maintenance: The Strategy of Periodic Maintenance".

- Foerli, O.; "Non-Destructive Testing Under Water". Paper No. 83 P002, June 1983.

- Sletten, R. (DnV), Ringard, M. and Torsen, H.O. (Continental Shelf Institute); "Trends in Underwater Operations with Special Reference to Inspection and Repair of Offshore Installations".

- Sletten, R.; "Underwater NDT - A Tool for Offshore Maintenance and QA". Second Nordiske NDT Symposium, Copenhagen, May 1979.

- Foerli, O.; "Inspection Methods - Equipment, Application and Development, Conference on Inspection and Condition Monitoring of Fixed Marine Constructions". Norway, January 1982.

- "Offshore Inservice Inspection and Monitoring - A Basis for Efficient Operation and Maintenance", Veritas Conference, November 1979, Hoevik, Norway.

- Dalberg, P.; "A Four Probe Technique for Accurate Sizing using Ultrasonic Diffraction", Paper No. 81 P105, November 1981.

- Hoegmoen, K. and Haugen, R.; "A New Ultrasonic Wheel Probe". Paper No. 81 P052.

- Hansen, O.K., Foerli, O. and Rangnes, E.; "Automatized Ultrasonic Equipment for Underwater Corrosion Inspection". Paper No. 80 P049.

- "Veritas' Underwater Trials Area (UWTA)". January 1980.

- "Underwater Testing and Training - Brief Introduction to Testing and Training Possibilities", December 1981, Bergen, Norway.

- "Qualifying Underwater Inspectors". VERITAS, No. 106-Oslo-1982-II.

- "Internal Corrosion Monitoring". VERITAS, No. 106-Oslo-1982-II.

- "ROVs for Underwater Inspection". VERITAS, No. 106-Oslo-1982-II.

- Skarsaeterhagen, A.; "R & D Project: Certification Scheme for Welding Inspectors". Veritas Report No. 83-0826, 1983.

- Moeller, O. and Bragaa, O.; "Comments on the Applicability and Qualification of UT-Operators According to API RP 2X and Specification D003-N-SS-005". March 1983.

- Hatlo, J.; "Application of Underwater Testing". British Journal of Non-Destructive Testing, 21, 6, 1979.

- Walter, J.C., Valland, G. and Onsvaag, E.; "New Trends in the Application and Evaluation of Non-Destructive Testing". International Conference on Quality Control and Non-Destructive Testing in Welds, London, England, 1, 1974.

- Saebjoernsen, K. and Foerli, O.; "Underwater NDE Technique". Materials Evaluation, April 1983.

- Det norske Veritas, Rules for the Design, Construction and Inspection of Offshore Structures, Appendix I, 1977 (with corrections 1981).

- Det norske Veritas, Technical Note A 801, Approval of Underwater Inspection Procedures, 1983, Rev. 0.

- Det norske Veritas, Technical Note A 802, Certification of NDE Equipment for Underwater Inspection, 1983, Rev. 0.

- Det norske Veritas, Technical Note A 803, Qualification of Underwater Inspection Personnel, 1983, Rev. 0.

8.3 General Bibliography

- International Institute of Welding; "Information on Common Practices for Underwater Non-Destructive Testing". DOC. V-745-83, June 1983.

- Farley, J.M. and Dikstra, B.J.; "Review of the Basic Capabilities and Limitations of NDT Techniques Used for Inspection of Offshore Structures". European Petroleum Conference, 1982, Paper No. 333.

- Youshaw, R. and Dyer, C.; "Underwater Non-Destructive Testing of Ship Hull Welds". Ship Structure Committee, U.S. Coast Guard Headquarters, September 1979, Paper No. SSC-293.

- Amiot, P.; "Inspection and Performance of Underwater Welds". International Institute of Welding Annual Assembly, Underwater Welding Conference, Trondheim, Norway, June 1983.

- "Eddy Current Detector". Underwater Systems Design, June/July 1981.

- The Welding Institute; "CP/E/1341 - Optimised Magnetic Particle Inspection Techniques for Welded Joints". May 1983, London, England.

- Silk, M.G.; "The Transfer of Ultrasonic Energy in the Diffraction Technique for Crack Sizing". Ultrasonics, May 1979.

- Lovell Smith, A.; "Underwater Visual Inspection". Journal of the Society for Underwater Technology, 8, 3, 1982, pp. 5-6.

- Munro III, J.J.; "Gamma Ray Sources for Industrial Radiography". C.S.N.D.T. Journal, 3, 4, 1982.

- Certification Scheme for Weldment Inspection Personnel, Document No. CSWIP-DIV-7-83, 2nd Edition, 1983.

- Aastroem, K.T.; "The Nordtest Certification Scheme for NDT-Personnel". 10th World Conference on Non-Destructive Testing, pp. 211-217.
- Duffy, D.E.; "Underwater Inspection: Theory and Practice". Potter, N.; Heyden and Son Ltd., London, 1981.
- Webborn, T.J.C.; "Systems for Inspection and Remote Crack Detection". Oceanology International 80 Proceedings, 1980, pp. 26-31.
- Allen, K.P.; "Further Considerations for NDT Validity and Structural Integrity". Offshore Inspection Repair and Maintenance Proceedings 1981.
- American Petroleum Institute Recommended Practice for Ultrasonic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Ultrasonic Technicians, Recommended Practice API RP 2X, 1980.
- Collins, H.D. et al.; "Acoustical Holography Matrix Array Imaging System for the Underwater Inspection of Offshore Oil Platform Weldments", Acoustical Imaging, 8, 8th International Symposium, 1978.
- King, M.J.; "Search Continues for Faster Detection Equipment". Offshore Oil Weekly, July 1980.
- "Ultrasonic Technique Speeds Crack Detection", Gas World, July 1982, pp. 7.
- Mittleman, J. and Wyman, D.B.; "Underwater Inspections: Credibility and Technology", Offshore Technology Conference, 1981, 2, pp. 207-210.
- MacLeod, C.J., Pearson, J. and Hayward, G.; "Processing Techniques for the Inspection of Offshore Structures". Conference on Acoustical Speech Signal Processing, 2, 1981.

- Browne, R.D., Doyle, V.J. and Papworth, F.; "Inspection and Repair of Offshore Concrete Structures", European Petroleum Conference, 1980, Paper No. 220.
- Rodriques, P.E.L.B., Wong, W.K. and Rogerson, J.H.; "Weld Defect Distributions in Offshore Platforms and Their Relevance to Reliability Studies, Quality Control and In-Service Inspection". Offshore Technology Conference, 1980, Paper No. 3693.
- Allen, K.P.; "Underwater NDT - Problems and Solutions", World Conference on Non-Destructive Testing, 1979, Paper No. 2A-13.
- Busby, R.F.; "Underwater Inspection/Testing/Monitoring of Offshore Structures", Ocean Engineering, 6, 4, 1979.
- Stumm, W.; "Magnetic Stray Flux Techniques in Non-Destructive Testing - Theory, Application, New Developments". British Journal of Non-Destructive Testing, 21, 4, 1979.
- Edwards, W.R. and Hargreaves, D.M.G.; "Five Year Underwater Inspection Program of a North Sea Steel Platform Jacket". Offshore Technology Conference, 1, 1979.
- Jackson, H.; "New Ultrasonic Tool Checks Offshore Pipeline Welds". Oil and Gas Journal, 76, 11, 1978, pp. 78.
- McEwan, W.; "NDT and the Underwater Environment". British Journal of Non-Destructive Testing, 20, 1, 1978, pp. 18-20.
- Peters, V.A.; "Offshore Platform NDT Instrumentation Requirements". Institute of Physics Conference, London, England, 34, 1977, pp. 13-18.

- 8th World Conference on Non-Destructive Testing, 1976.

- Browne, R.D., Domone, P.L. and Geoghegan, M.P.; "Inspection and Monitoring of Concrete Structures for Steel Corrosion". Offshore Technology Conference, 1977, Paper No. 2802.

- Goodfellow, R. and Bourne, M.J.; "Underwater Inspection of Deep Water Facilities", Petroleum Engineer, 48, 7, 1976, pp. 11-12.

- Alia, B.L., Wheatcroft, M.F. and Null, C.L.; "Material Selection, Welding and Non-Destructive Testing Guidelines for Offshore Mobile Drilling Units". Offshore Technology Conference, 1976, Paper No. 2647.

- Peters, V.A., Davies, D.M. and Hughes, B.G.; "Role of Non-Destructive Testing in the Offshore Oil and Gas Industry". Weld in Offshore Constructions Conference, 1974, 1, pp. 205-213.

- Silk, M.G., Williams, N.R. and Bainton, K.F.; "Potential Role of NDT Techniques in the Monitoring of Fixed Offshore Structures". British Journal of Non-Destructive Testing, 17, 3, 1975, pp. 83-87.

- Lawton, T.R.; "Inspection of Underwater Structures", Petroleum Review, 24, 288, 1970, pp. 393-395.

- Hung, Y.Y. and Grant, R.M.; "Non-Destructive Testing of Offshore Structures by Shearography", Behaviour of Offshore Structures, Vol. 2, Hemisphere Publishing Corp., 1982.

- Herve, J.L., Ling, M.T.S. and Undeli, J.; "Frigg Pipeline System uses New Inspection Techniques". Pipeline Industry, March 1982.

- "NDT Adapted for Underwater Use". J. Inst. Eng. Aust., August 1980.
- Rogers, L.M., Hansen, J.P. and Webborn, T.J.C.; "Application of Acoustic Emission Analysis to the Integrity Monitoring of Offshore Steel Production Platforms". Materials Evaluation, August 1980.
- Rutherford, P.; "Inspection, Repair and Maintenance Offshore - What are the Training Requirements". Jernindustri, November 1979.
- Edwards, G.R.; "Ultrasonics in the North Sea Oil Industry", Anticorros. Methods Mater., December 1979.
- Mittleman, J.; "Underwater Ship Hull Inspections". Gateway to NDT Technology, American Society for NDT, 1979.
- Muir, G.; "Certification for In-Water Survey and Inspection". British Journal of Non-Destructive Testing, September 1979.
- Britton, C.F.; "Monitoring of Internal Corrosion in Offshore Installations". Mar. Eng. Rev., January 1979.
- Stankoff, A.G. and Collins, D.H.; "Application of Acoustical Holography to the Inspection of Offsore Platforms". Offshore Technology Conference, 1978, 4.
- "Underwater Inspection - Offshore Structures", Weld. Des. Fabr., September 1977.
- ONeill, T.J.; "Underwater Inspection by Divers", Proc. Conf. on Long Service from Offshore Structures, 1976.
- Sansom, W.H.; "Non-Destructive Testing, Pt. 6, Underwater NDT Techniques". Welder, 40, 193, pp. 16-18.

- Jones, H.W. and Miles, H.T.; "Development of Ultrasonic Image Converters for Underwater Viewing and Other Applications". Ocean Engineering, July 1969.
- Junke, H.; "Underwater Wall-Thickness Measurements and Weld Testing by Ultrasonics". 5th International Conf. on Non-Destructive Testing, Ottawa, Canada, 1969.
- Lambert, G.; "An Application of Underwater Radiography". Materials Evaluation, March 1968.
- Atteraas, L., et al.; "Underwater Technology - Offshore Petroleum, Pergamon Press, 1980.
- "Magnetic Particle Testing in the Marine Environment". Materials Evaluation, April 1983.
- Carnevale, S.; "An Introduction to Atmospheric Diving Suits". Materials Evaluation, April 1983.
- Galerne, A. and Walker, D.; "Deep Water: The New Frontier for NDT". Materials Evaluation, April 1983.
- Anderson, C.C.; "A Review of Structural Inspection and Maintenance Experience at Ekofisk", Veritas Conference: Offshore Inservice Inspection and Monitoring, Oslo, 1979.
- An Assessment of Underwater NDT Equipment, Phase I (1981), Phase II (1982), DOE Project No. 538.
- Webborn, T. J.C., et al.; "Acoustic Emission Monitoring Techniques Applied to Offshore Structure - Subsea and Topside Applications". European Offshore Petroleum Conference, 1980, Paper No. 252.

- Tang, W.H.; "Probabilistic Updating of Flaw Information", ASTM, Journal of Testing and Evaluation, 1, 6, 1973.
- Loland, O. and Dodds, C.J.; "Experiences in Developing and Operating Integrity Monitoring Systems in the North Sea". Offshore Technology Conference, 1976, Paper No. 2551.
- Peterson, D.K., Bennett, S.D. and Kino, G.S.; "Real-Time NDE of Flaws Using a Digital Acoustic Imaging System". Materials Evaluation, 40, 11, 1982.
- Schmitz, V., Mueller, W. and Schaefer, G.; "A New Ultrasonic Imaging System". Materials Evaluation, 10, 1, 1982.
- Segal, E., Notea, A. and Segal, Y.; "Dimensional Information Through Industrial Computerized Tomography". Materials Evaluation, 40, 12, 1982.
- Burstein, P., Mastronardi, R. and Kirchner, T.; "Computerized Tomography Inspection of Trident Rocket Motors: A Capability Demonstration".
- Dumousseau, P.F., Laffont, P. and Thebault, J.M.; "Experimental Study of Acoustic Emission Monitoring of Crack Propagation in Offshore Steel Tubular Joint". Offshore Technology Conference, 1979, Paper No. 3425.
- Murray, I.J. and Bewley, E.; "Structural Inspection from an Underwater Engineering Contractor's Viewpoint". European Petroleum Conference, London, 1982.
- The Welding Institute; "Size Measurements and Characterization of Weld Defects by Ultrasonic Testing, Part 2". Welding Institute Cambridge, 1982.

9. APPENDICES

APPENDIX A
NDE EQUIPMENT DESCRIPTIONS AND SPECIFICATIONS

APPENDIX B
ON-GOING NDE RESEARCH PROJECTS IN THE UK

APPENDIX A

NDE EQUIPMENT DESCRIPTIONS AND SPECIFICATIONS

The principal components of NDE equipment currently used in offshore inspections are presented here.

The purpose of this appendix is to provide information on the hardware deployed for detection and measurement. It is beyond the scope of the study to compile an operational manual for the equipment.

Information source for this appendix has mainly been the literature supplied by the manufacturers.

A.1 Visual Inspection

Results of direct visual inspection are often recorded using photographs and/or video recordings. There are various systems currently available; two of these are the Nikonos underwater camera and the OSEL Hydroscan camera.

While the Nikonos is a sport diver's camera which can be used for weld photography, the Hydroscan camera (costing approximately CAD $8,500, converted from UK pound sterling) has been specifically designed for that purpose. Both cameras can be outfitted with stand-off prods to permit quick and accurate positioning over the surface to be photographed. To obtain the required photograph, the weld is cleaned and an appropriate magnetic particle inspection technique is used together with fluorescent ink. By using fluorescent inks, defects stand out vividly under ultraviolet light. However, as the amount of white (ambient) light increases, the contrast between defect and weld decreases, which only becomes a problem near the water surface.

Video is used by observers on the surface to check the work done by divers as well as for monitoring the general condition of structural parts. However, the video image normally lacks the resolution and quality that is required for detailed examination purposes. In the case of defects, it is therefore a common requirement to take colour photographs. This may be difficult when visibility in the water is very low. In such cases a low light intensity TV camera may be the best aid to a skilled diver. Stereo photographs provide additional information that aids interpretation of the findings.

A .2 Equipment Based on Electromagnetism

A.2.1 MPI

MPI systems manufactured for underwater application typically consist of three major components:

- a subsea unit;
- a surface control unit;
- an underwater U/V lamp.

The subsea unit has a pressure compensating housing, containing a transformer, power supply to the ultraviolet lamp, and a motor drive for the ink circulating system.

Connected to the subsea unit through a single umbilical cable, the surface control unit receives power from the transformer.

The underwater U/V lamp is also connected to the subsea unit through an umbilical which carries the constantly agitated magnetic ink fluid that is directed onto the area under examination by a nozzle through a control valve positioned in the lamp handle enabling single handed operation.

Underwater magnetisation can be safely achieved utilising either prod, coil conductor or electromagnetic yoke techniques described in Section 2.1.2.1.

Specifications for MPI systems manufactured by OIS and OSEL are included in Table A-1.

The equipment used with the Magfoil method, is the Flexiyoke EL60T manufactured by Henrichs & Walther GmbH, West Germany. The Flexiyoke EL60T features a fully flexible yoke magnet with easy adaptation to complex geometries. At a pole spacing of 170mm it gives a current density of 12 kA/m. The poles can be separated to more than 250mm, depending on geometry, and the flux density of 4 kA/m obtained will still be sufficient for reliable indications of the smallest flaws.

TABLE A-1
TECHNICAL SPECIFICATIONS FOR MPI EQUIPMENT
(Taken from manufacturers' brochures)

Dimensions	OSEL MPI	OIS Compact	OIS MkII
Surface Unit (mm x mm x mm)	362 x 527 x 305	350 x 250 x 255	480 x 250 x 250
Submersible Unit (mm x mm x mm)	647 x 317 x 457	310 x 240 x 285	Ø 260 x 450
UV Lamp	230 x 93 x 200 mm x mm x mm	Ø 120 x 210 mm x mm	Ø 120 x 210 mm x mm
Weights in Air			
Surface Unit	14 kg	26 kg	35.5 kg
Submersible Unit	78 kg	18 kg	56.8 kg
UV Lamp	2 kg	2.25 kg	3.5 kg
Weights in Water			
Submersible Unit	40 kg	9.5 kg	26 kg
UV Lamp	1 kg	0.5 kg	0.5 kg
Depth Rating			
Submersible Unit	305 m	No Limit*	No Limit*
UV Lamp	305 m	200 m	200 m
Electrical Supply	210/250 VAC, single phase, 36 Amp	110/120 or 220/240 VAC, single phase, 13 Amp	210/240 VAC, single phase, 30 Amp
Electromag. yoke	-	Articulated 12VDC	Articulated 5VAC or DC
Prods	1500 Amp AC or DC, variable output, open circuit at 8V	-	1500 Amp AC or DC, variable output, open circuit at 5V
Coil or Cable	55 ft. cont. loop, 1000 Amp AC or DC, 5V duty cycle	-	40 ft. cont. loop, 1000 Amp AC or DC, 5V duty cycle
Approximate Cost	CAD $35,400 (CAD price quote)	CAD $9,000 (converted from UK pound sterling)	CAD $16,500 (converted from UK pound sterling)

* due to oil filled pressure compensating housing.

A.2.2 Magnetography

Subsea components include two different yokes for various weld geometries, underwater power supply, tapes, fixing magnets, and auxiliary parts, Figure A-1a. The underwater power supply has an operational depth of 300m and lasts for an entire one-day operation before recharging is required. At present, the subsea equipment can be applied at nearly any position in dry zone, splash zone, or underwater to depths of 300 meters.

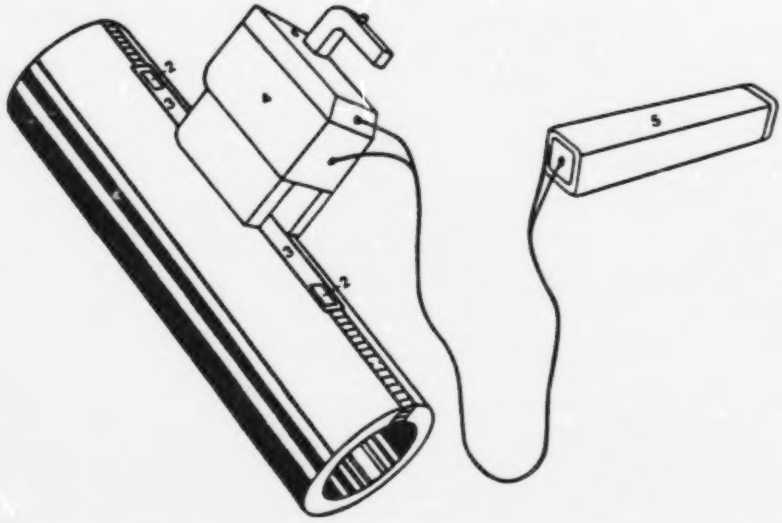
The above water evaluation system comprises three major components, Figure A-1b one of these is the power supply box with safety circuits, battery charger, and tape eraser tunnel. The second component is the tape scanner with calibrated tape tracking drum, amplifiers, and filters. The third unit gives scope representation and strip-chart recordings of the actual defect signals.

A.2.3 EMD

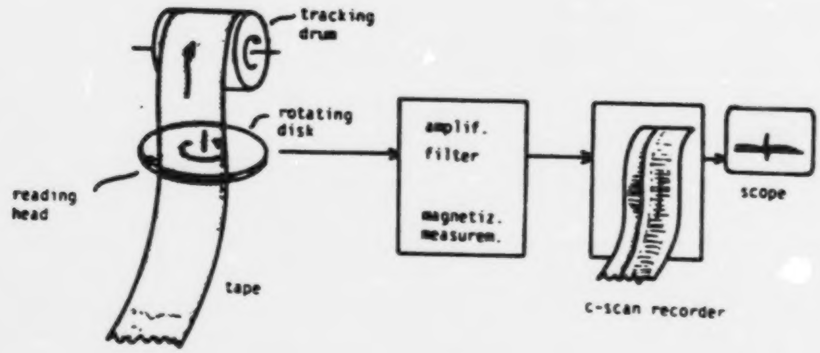
The EMD system manufactured by Thorburn Technics consists of an above water oscilloscope type unit and underwater probes connected to the unit by armoured cable of up to 350m. Equipment specifications are given in Table A-2.

A.3 ACPD Measurement

To provide for instantaneous calibration, and a direct display of crack depth, a microprocessor has been used in the ACPD unit developed by DnV. Once turned on, the processor will start to operate as soon as sufficient contact of the probe contacts has been obtained. The calculated crack depth is then indicated on a built-in LED display. In addition, the battery state is checked.



a) 1) Weld; 2) Permanent Magnet; 3) Tape; 4) Yoke; and 5) Power Supply.


tracking drum
rotating disk
reading head
tape
amplif.
filter
magnetiz.
measurem.
c-scan recorder
scope

b) Magnetograph Tape, Scanning and Recording Scheme

Figure A-1 Magnetographic Equipment

(Taken from: Stumm, W.; "Magnetographic Weld Inspection System for Underwater Installations". Materials Evaluation, April 1983).

TABLE A-2
EMD EQUIPMENT
(Taken from manufacturer's brochures)

Specifications	Thorburn Technics EMD III Deep Sea
Dimensions (mm x mm x mm)	600 x 225 x 320
Weight in air:	18.0 kg
Power:	240 V or 120 V 48-440 Hz 90 W max.
Operating temperature:	0 degrees C to 40 degrees C
Cable:	Armoured; 150 m to 350 m lengths in 50 m increments
Probe bodies:	Straight or Right angle
Probe tips:	Intermediate, ø 7.5 mm
Pencil Point:	ø 1.73 mm
Approximate Cost:	CAD $26,500 (converted from UK pound sterling)

In order to maintain the exact potential contact spacing, a special probe has been designed. The depth of surface-breaking cracks in the weld or between the weld and base material of offshore tubular joints can be measured with this equipment. The whole system can be normally operated by one diver as the probe and the electronic container are attached to the structure by holding magnets while the crack area is magnetized with the prod method as used with MPI.

Another system, the OSEL Underwater Crack Microgauge, consists of a number of components including a subsea unit with battery pack, underwater probes, surface read-out unit, and umbilical cable for surface read-out. The subsea unit is fitted with powerful magnetic clamps so that it can be positively located on the structure being inspected, as are the two probes used to establish the A.C. field. Once the unit is fixed in position, the only operation required from the diver is manipulation of the measuring probe.

The subsea unit display, which is repeated on the surface read-out unit, consists of a digital read-out of potential plus 2 LED indicators. One LED shows when the A.C. field has been properly established, the other when good measuring probe contact has been achieved.

Power for the subsea unit is provided by a rechargeable battery pack which is replaceable underwater. The capacity of the fully charged battery pack is sufficient for 4 hours of continuous operation.

Technical specifications for the OSEL system are given in Table A -3.

A .4 Ultrasonic Testing

.4.1 Probes

MatEval Ltd., U.K. is one designer and manufacturer of ultrasonic probes offering a comprehensive range of standard transducers. MatEval Ltd. also has the capability of designing probes for specific applications requiring immersion transducers, multi-element transducers and phased-array systems.

TABLE A.-3
ACPD EQUIPMENT SPECIFICATIONS
(Taken from manufacturer's brochures)

Specifications	OSEL Underwater Crack Microgauge
Subsea unit dimensions (mmxmmxmm):	480 x 210 x 210
Surface unit dimensions (mmxmmxmm):	140 x 90 x 100
Operating depth:	305m
Weight in air:	18 kg
Weight in water:	9 kg
Measuring probe:	10 mm or 15 mm spacing
Field probe spacing:	200-300 mm either side of defect
Batteries (subsea unit)	12-1.5 V alkaline cells
AC field:	Approx. 2 Amps at 6 kHz
Measurement range:	0.1 mm min. on smooth surface 1.5 mm min. on rough surface
Accuracy:	10% of measured depth
Approximate Cost:	CAD $18,000.00 (converted from UK pound sterling)

In addition to MatEval Ltd., Harisonic Laboratories Inc., Connecticut, U.S.A., Panametrics Inc., Massachusetts, U.S.A. and Krautkramer Branson, Pennsylvania, U.S.A. are also major manufacturers of ultrasonic probes.

A.4.2 Thickness Measurement

Considering the application to underwater NDE, thickness measuring equipment can be categorized in two ways: units that have been designed specifically for the underwater application or compact above water units which can be encapsulated in watertight housings. (These watertight housings are manufactured by diving contractors or offshore NDE equipment suppliers). Two units falling into the former category are the WK-DMU designed by Wells-Krautkramer for Krautkramer Branson and the Baugh & Weedon SP200 Seaprobe.

Both the WK-DMU and the Seaprobe are hand held units activated by pressing the spring loaded transducer against the surface of the material to be measured.

Two units which may be encapsulated in underwater housings are the Nortec 123U and Panametrics model 5222UG. Using these devices, a probe connected to the unit by a cable is pressed against the surface to be measured.

For all units, the thickness readout is immediate and is presented to the diver on either a LCD or LED display. The diver then either records the information or relays the readings verbally to the surface.

Specifications for these units are included in Tables A-4 and A-5.

TABLE A-4

ULTRASONIC UNDERWATER THICKNESS GAGES

(Taken from manufacturers' brochures)

Specifications	Baugh & Weedon SP200 Seaprobe	Krautkramer Branson WK-DMU
Size (mmxmm)	Ø 85 x 360	Ø 80 x 310
Weight in air:	1.5 kg	1.5 kg
Thickness measuring range:	5.0mm-99.9mm in steel	4.0mm-99.9mm in steel
Accuracy:	±0.2mm	±0.1mm
Operational temperature:	-5 to 50 degrees C	-
Pressure tested depth:	200m	180m
Display:	3 digit LED	3 digit LED
Battery:	rechargeable 6V nickel-cadmium	rechargeable five 1.5V cells
Battery life:	2000 readings	8 hours continuous operation
Battery Charging time:	-	16 hours max.
Approx. Cost:	CAD $3,600 (Canadian Price)	CAD $6,200 (converted from US $)

TABLF A-5

ENCAPSULATED ULTRASONIC THICKNESS GAGES FOR UNDERWATER APPLICATION

(Taken from manufacturers' brochures)

Specifications	Panametrics 5222UG	Nortec 123U
Encapsulated Size (mmxmmxmm):	93 x 181 x 264	121 x 76 x 229
Weight in air:	8.1 kg	2.0 kg
Thickness	3.0mm-99.9mm in steel	1.3mm-254mm +
Resolution:	±0.01mm	±0.03mm max
Operational temperature:	0 to 50 degrees C	-
Pressure tested depth:	305m	105m +
Display:	4 digit LED	LCD
Battery:	rechargeable, 6V solid gel	rechargeable Nickel/Cadmium
Battery life:	8 hours continuous operation	10-12 hours continuous operation
Battery charging time:	16 hours max.	12-14 hours max.
Housing:	Welded aluminum	G.E. Lexan polycarbonate
Approx. Cost:	CAD $5,500 (converted from US $)	CAD $4,600 (Canadian price quote)

A.4.3 Flaw Detection and Sizing

Ultrasonic flaw detectors used underwater are above water units encapsulated in underwater housings. Several above water models are currently used for underwater NDE, including Baugh & Weedon's Ten Eleven S and Krautkramer Branson's USK7. Both units, once they've been encapsulated, are designed to be diver-held and self-powered; information is displayed on a CRT but no provisions have been made for recording the display. Interpretation of the display is consequently left to the diver. Specifications for both detectors are given in Table A-6.

A Subsea Ultrasonic Repeating System (SURS II) which permits interpretation by an NDE technician other than the diver is manufactured by Oilfield Inspection Services (OIS), Aberdeen in conjunction with Baugh & Weedon. SURS II is available in three combinations:

SURS II, System 1: Consists of a transmitter (Baugh & Weedon Ten Eleven S) encapsulated in a cast aluminum housing for underwater use, a surface receiver (Baugh & Weedon Ten Eleven S, not encapsulated) and the required umbilical between the units. Using this combination, the diver takes the measurements using the subsea unit; information is subsequently displayed on the diver's unit (transmitter) and is repeated on a surface unit (receiver) simultaneously. The diver therefore need not necessarily be a qualified NDE technician. Both units may be used independently for standard subsurface or surface ultrasonic testing. The operational depth for the subsea unit is 300m.
Cost: CAD $42,000, approx. (Canadian price quote).

SURS II, System 2: Is a single Ten Eleven S flaw detector encapsulated in the underwater housing for use subsea as a conventional flaw detector. This unit does not have transmit/receive capability.
Cost: CAD $19,000, approx. (Canadian price quote).

TABLE A-6

ENCAPSULATABLE ULTRASONIC FLAW DETECTORS FOR UNDERWATER APPLICATIONS

(Taken from manufacturers' brochures)

Specifications	Baugh & Weedon Ten Eleven S	Krautkramer Branson USK7
Encapsulated: Size (mmxmmxmm)	130 x 180 x 270	95 x 240 x 300 (without UW housing)
Weight in air:	5.6 kg	5.3 kg
Working temperature: (degrees C)	-15 to +50	-15 to +40
CRT display size:	70mm x 55mm	70mm x 55mm
Operating Frequency range:	0.5 MHz to 15 MHz	0.5 MHz to 10 MHz
Operating mode:	single, double, separate transmit.-and-receive	single or dual probe and thru-transmission
Test range:	10mm - 7m in steel	10m - 2.5m in steel
Battery:	rechargeable, NiCad	rechargeable, NiCad
Operating depth:	200m	-
Approx. Cost:	CAD $4,200 (Canadian price quote)	CAD $5,400* (Converted from US $)

* without housing.

SURS II, System 3: Has the same capability of System 1 with additional features. Both the transmitter and receiver are encapsulated for use subsea. Disconnection of the umbilical between units automatically converts both to conventional flaw detectors and they may therefore be used independently of each other when repetition of information on another unit is not required.
Cost: CAD $48,000, approx. (Canadian price quote).

For systems 1 and 3, up to 500m of umbilical may be used between flaw detectors.

Operated separately, the flaw detectors have a battery life of about 5 hours; used together, battery life reduces to approximately 4-1/2 hours.

A.4.4 Corroscan

Corroscan is equipment consisting of an automated scanner and above water control unit designed to monitor internal corrosion of pipelines, risers and other important equipment. The underwater scanner moves around the pipe on a chain, and ultrasonic signals as well as position signals for the transducer are transmitted through cables to a registration and processing system above water. Inspection results are available in real time, and all data are stored on magnetic tape for later analysis.

A.4.5 Ultrasonic Torch

The Ultrasonic Torch is a system which provides rapid screening of welds for the presence of cracks. It is capable of detecting all surface opening cracks above a predetermined size (eg. 20 mm long by 3 mm deep) and is capable of identifying their positions.

The Ultrasonic Torch system consists of three major components:

a) an underwater measuring device;
b) an underwater power supply and signal processing unit; and
c) a surface display console.

The measuring device (a pressure equalised measuring head mounted on the end of a short handle) sends signals to the power/signal processing unit which subsequently transmits the processed signals to a display console above water.

The measuring device (fitted with stand-off prods) is operated by a diver by placing the device on the surface of the member on which measurements will be made. The measuring head contains sensors which sense the proximity of the member under inspection and, by means of miniature closed loop servos, align a gimballed platform in a precise attitude relative to this member. Mounted on the gimballed platform is a specially designed ultrasonic transducer which scans the surface of the member and produces signals giving information about the position of the transducer relative to the inspected surface, and about defects in or near the welds.

While an A-scan display can be provided by the display console, the scanning transducer and signal processing equipment permit real-time mapping of the area under inspection. A permanent record of the inspection may then be obtained by photographing the display.

A.5 Radiographic Testing

A compact gamma radiographic unit jointly produced by OIS and CS Products is the Nautilus. The Nautilus is capable of holding up to 200 curies of Iridium 192 and has a depth rating of 750 m. The actual source is housed in a depleted uranium rotational chamber which is air-actuated from the surface to ensure safe working conditions, for those involved. The cost of the Nautilus unit is approximately CAD $12,000 (converted from UK pound sterling) but does not contain radioactive material as delivered by OIS.

Radiation monitoring is necessary when using Nautilus. This can be accomplished using a monitor such as the Graetz Gamma 100B from OIS which is encapsulated in an underwater housing. OIS is however developing a new model which will be available in 1984 at an approximate cost of CAD $1,500 (converted from UK pound sterling).

Additional equipment consists of a remote surface readout system giving a metered display which permits video recording of radiation levels.

A6 Remotely Operated Vehicles and Atmospheric Submersibles

In the previous sections, NDE methods and equipment have been described which require the involvement of divers directly. This chapter deals with underwater operations where either the inspection is carried out by manned submersibles (where the operators are at atmospheric pressure) or by unmanned remotely operated vehicles (ROV's).

A.6.1 Manned Submersibles

Under this heading, further classifications are required owing to two different concepts: manned underwater vehicles and atmospheric diving suits.

A.6.1.1 Manned Vehicles

Manned vehicles are one of the next best ways of taking man and NDE equipment to the testing site. Some of these vehicles can hold several persons; one vehicle which can accomodate 5 persons to depths of 2000 ft. is the 17-ton Beaver. Two two-man vehicles are the Mermaid (operating at depths to 1000 ft.) and the 12-ton Pisces (rated to 8300 ft.). Mantis is a one-man vehicle which can dive rapidly to depths over 2000 ft. and perform tasks using strong manipulator arms.

A.6.1.2 Atmospheric Diving Suits (ADSs)

Atmospheric diving suits are a development of Oceaneering International and provide an alternative to deep water diving. Oceaneering has developed three models: the JET JIM, Wasp, and Wasp Inspector ADSs. The JET JIM features a 610 m depth capability, four 1.5 kW AC motors with variable pitch propellers, foot-operated thruster controls, 2-knot current bottom capability, and variable 0-60 lbs. buoyancy. Capabilities of the suit include video and still photography, anode replacement, NDT, cathodic protection measurement, 3-dimensional visual inspection and a variety of other repair, maintenance, and retrieval tasks. The size of the suit is 78" x 56" x 44" and weighs 780 lbs. in air thereby necessitating a vehicle launch/recovery system. Both the Wasp and Wasp Inspector have similar capabilities.

In the case of the Wasp, the deployment system consists of a cage or garage supporting the ADS that is lowered to the required working depth. Once this depth has been reached, the Wasp can be released and move about employing a lighter umbilical than would be possible without such a deployment cage.

A.6.2 Remotely Operated Vehicles (ROVs)

For visual inspection tasks and photographic work, ROVs frequently replace divers because of the unlimited amount of time they can remain underwater and the great depths to which they can dive. (One example, the Epaulard, is totally autonomous and can do photographic and bathymetric surveys down to 20,000 ft.). Generally ROVs are powered through umbilicals and can maneuver in small spots because of their small size.

Besides visual inspection, ROVs can carry out cathodic potential readings on structures and pipelines, and measure bury depths along buried pipeline routes. In the North Sea, upgraded ROVs are equipped with one or two black-and-white low light high-resolution TV cameras, a colour photographic camera, accurate depth sensor, heading sensor, pipetracker, cross trench profiler, and reference electrode for cathodic potential measurements. Results from surveys performed by these vehicles were found to have the same quality as those previously obtained from manned submersibles.

One such ROV is the Hydro-Products RCV-225. This vehicle can perform detailed underwater inspections to depths of 2,000 m. In addition to the vehicle itself, the RCV-225 system also consists of a deployment unit and a control van.

The deployment unit includes a protective ROV launcher with tether cable winch and a hydraulic power supply. The vehicle is transported to working depth in the launcher, performs the inspection task, and then returns for transport back to the deck. The vehicle can also be deployed from launchers attached to manned submersibles, diving bells, upper stacks, marine risers or guide wires.

The control van houses video tape recorders with monitors, a video control console and the vehicle control console. Depth, heading, lens pitch angle and other data are displayed on the television screen and recorded.

Performance characteristics, and size and weight data for the RCV-225 system are included in Tables A-7 and A-8.

TABLE A-7
RCV-225 SYSTEM SIZE AND WEIGHT
(Taken from manufacturer's brochures)

		Size			Weight	
Component	Location	Height	Width	Depth	Air	Water
Vehicle	U/W	51cm 20 in	66cm 26 in	51cm 20 in	82kg 180 lbs	-2kg -4 lbs
Control Station	Topside	80cm 31 in	56cm 22 in	78cm 30 in	158kg 350 lbs	-
Deployment Unit:						
Winch/skid/A-frame[1]	Topside	1.8m 6.0 ft	1.4m 4.5 ft	2.3m 7.5 ft	1980kg 4355 lbs	-
Hydraulic PS	Topside	0.8m 2.5 ft	0.6m 2.0 ft	0.9m 3.0 ft	200kg 440 lbs	-
Underwater launcher[2]	U/W	1.1m 3.7 ft	1.0m 3.2 ft	1.0m 3.2 ft	193kg 425 lbs	175kg 385 lbs

1. With 400m (1350 ft) armored cable.
2. With 120m (400 ft) tether cable.

TABLE A-8

RCV-225 VEHICLE PERFORMANCE

(Taken from manufacturer's brochures)

	Ability to Maintain Position	
Orientation of Vehicle	Without High-Thrust Package	With High-Thrust Package
Into current (Forward)	1.25 knots	2.0 knots
Transverse	0.75 knots	1.1 knots
Reverse	1.2 knots	1.9 knots

Two systems similar to the RCV-225 are the Canadian built Dart and Trec systems from International Submarine Engineering.

Inspection of construction joints and high stress areas on concrete platforms often requires cleaning of marine growth from these areas. For this purpose larger ROV's have been fitted with hydrojects and telescopic suction pads (to keep the vehicle steady during the cleaning operation). These cleaning vehicles also possess one or two manipulator arms fitted with single jets to clean difficult areas. ROV systems that perform these cleaning tasks are the Snurre 1 and Snurre 2 by Myrens Verksted, Norway.

A.7 Prospective Inspection Equipment

A.7.1 Advanced Ultrasonic Testing

A.7.1.1 P-Scan

Based on P-Scan, DnV CORROSCAN for mapping corrosion of pipelines and risers was developed.

A.7.1.2 Rotoscan

Using Rotoscan, multiple crystal probes (at various angles) are placed in two housings on each side of the weld so that the whole depth of weld is being scanned including the wall thickness. The number of crystals depends on wall thickness. Usually a 5mm zone is scanned by one transducer. The scanner is positioned using a band. Rotoscan uses an ultrasonic micro- or mini-computer based system SONOLOG (developed by RTD) for data logging and A-scan, B-scan or C-scan image generation.

A.7.1.3 SUTARS

Technical specifications for SUTARS are given in Table A-9.

TABLE A-9

SUTARS TECHNICAL SPECIFICATIONS

Number of receiving sensors	2 to 6, as needed
Maximum area coverage (sector)	8" (203.2mm) x 25" (635mm)
Cell size	0.2" (5.08mm) x 0.2" (5.08mm)
Cell location accuracy	0.1" (2.54mm)
Maximum number of cells/sector	5000
Maximum sensor spacing	5" (127.0mm)
Minimum sensor spacing	2" (50.8mm)
Minimum pipe diameter for inspection	2" (50.8mm)
Maximum pipe diameter for inspection	48" (1220mm)
Thickness measurement range	0.05" (1.2mm) to 4.0" (101.6mm)
Thickness measurement accuracy	±0.003" (0.076mm)
Search unit size	0.125" (3.175mm) to 0.5" (12.7mm) round
Data acquisition rate	30/second
Data processing, printing rate	1200 baud (120 characters/second)
Data processing, recording rate	4800 baud (480 characters/second)
System power requirement	Less than 1000 watts
Total system weight	Less than 200 lbs. (90.72 kgs)
Maximum weight/module	Less than 40 lbs. (18.14 kgs)

A.7.1.4 Time-of-Flight System

The present time-of-flight system developed by Harwell costs approx. CAD $100,000 and includes the probe assembly, control and data acquisition electronics and software.

A.7.1.5 TREES

Turbine Rotor Examinational/Evaluation System (TREES) equipment specifications are given in Table A-10.

A.7.1.6 Phased Arrays

The phased array system developed at the Fraunhofer Institute has 24 individually controlled channels and consists of a transmitter/receiver unit, a delay unit, a microcomputer and image display and uses three different types of transducer arrays: annular arrays, linear arrays and planar arrays.

A similar linear array real-time imaging system has been developed at Stanford University (USA).

A.7.1.7 Ultrasonic Holography

Advanced electronic equipment containing a transmitting and a receiving unit, a mechanical scanner which moves either a plane or a focused probe in rectangular coordinates or a linear array and a powerful computer system was developed at Fraunhofer Institute. The computer system drives a graphic terminal to supervise and display the recorded data so that a parallel data-acquisition, -reconstruction and -visualization is possible. Highly advanced signal processing techniques are used (satellite-pulse -technique, pulse orientation, time-of-flight locus curves, etc.) to reconstruct the defects.

TABLE A-10

TREES TECHNICAL SPECIFICATIONS

Number of Focused Search Units	12
Number of Conventional Search Units	3
Operating Frequencies	5-10 MHz
Mechanical Scanner Repeatability:	
Circumferential	±0.1 degrees
Axial	±0.01" (0.25mm)
Mechanical Scanner Speed:	
Axial:	
Examination	0.3" (7.62mm)/min
Rapid Advance	0-3' (0.91m)/min
Rotational	15 rpm
Examinable Bore Length	0-30' (0.91m)
Examinable Bore Diameter Range	3-13" (76.2mm-330.2mm)
Power Requirements:	
Computer	230 VAC, 60 Hz, Single phase 30 amps
Data Acquisition/Mechanical	110-120 VAC, 60 Hz,
Positioning	Single Phase, 1 amp

The system includes:

- real time imaging;
- electronic scanning;
- variable focal length;
- automatic sweep focus;
- manual focus;
- magnification zoom;
- three-dimensional display;
- interchangeable scanning heads;
- arrays of multiple transducers;
- diver monitor.

A.7.2 Enhancement of Electromagnetic Methods

Since new methods and systems being investigated at the UK Welding Institute and at Harwell are still in the development stage, descriptions of equipment cannot be provided.

A.7.3 Computerized Tomography

Recently the medical tomography equipment has been modified or new equipment built to be used as an industrial NDE tool. Further details may be found in Segal, 1982 and Burstein; refer to General Bibliography.

A.7.4 Enhanced Visual Inspection

A.7.4.1 CARTIS

Using CARTIS, a system computer is linked to a real-time image processor that accepts signals from a variety of sensors including television cameras, CCD (charge coupled devices) arrays and x-ray image intensifiers. Once the signal has been translated into electronic signals, the CARTIS system uses its software to enhance, detect, or make decisions on the image seen.

Real-time radiography using high frequency electronic generators with computer control to provide the quality and stability of output desired.

A.7.4.2 Optical Holography

Design features of an underwater holographic camera are discussed in the literature[3.7].

APPENDIX B

ON-GOING NDE RESEARCH PROJECTS IN THE UK

1. Title:

Evaluation of defects in members of structural frameworks using resonant vibration techniques.

Institution:

Newcastle University, Newcastle.

Investigator(s):

Dr. D.M. Lilley, Dr. J.W. Bull/Civil Engineering.

Overall Aims and Applications:

The aim of this project is to develop a vibration test technique for members of a structural framework, to determine the presence of any cracks and, if present, their exact position and severity.

The results will be in the form of a report, computer program giving graphical results, in-situ vibration test equipment and method (possibility of remote control). It is hoped this will be significant in assessing the safety of in-situ offshore (and onshore) structural frameworks.

2. Title:

Specific electrochemical sensors for precise measurement of chemical species in seawater.

Institution:

Newcastle University, Newcastle.

Investigator(s):

Dr. J.V. Dobson/Physical Chemistry.

Overall Aims and Applications:

Marine subjects compatible with electrochemical sensors and techniques will be identified and researched.

Electrochemical sensors may be studied for gases or metal ions (including pH) with a view to developing useful instrumentation to furnish in situ type data on factors associated with structural integrity and corrosion of metal structures and ships or seabed studies.

3. Title:

Characterisation of acoustic emission signals for improved structural monitoring role.

Institution:

Cranfield Institute of Technology, Cranfield, Bedford.

Investigator(s):

Mr. B.S. Hockenhall, Dr. J. Billingham; School of Industrial Science.

Overall Aims and Applications:

The acoustic emission technique has great potential for both localised and global structural integrity monitoring of offshore installations. Current drawbacks to the technique include the difficulties and high cost of installing and monitoring a properly engineered grouping of transducers offshore and the problems of identifying "real" danger signals from the signal response from the overall structure. The objective of the current work is to improve the correlation of certain unique acoustic emission signals with particular degradation processes and incorporating simpler pattern recognition features into field equipment.

4. Title:

Structural integrity monitoring offshore with optical fibre devices.

Institution:

Cranfield Institute of Technology, Cranfield, Bedford.

Investigator(s):

Dr. J. Billingham, Mr. B.S. Hockenhull, Mr. T.E. Clifton; School of Industrial Science.

Overall Aims and Applications:

Suitably treated optical fibres can be used as strain monitoring devices. This project will continue to develop such devices as fatigue crack growth monitors and as crack detectors at critical locations on offshore structures. The work will include developing appropriate optical fibre crack growth monitoring devices for use offshore on steel and concrete structures. This will include laboratory studies and realistic trials in marine environments. Such information should enable safer opeation and/or more effective inspection/maintenance programs to be carried out. Important aspects of the work will be to develop suitably sensitive packages for detecting small crack openings for early warnings of crack formation, assessing the suitability of such devices for monitoring underwater fatigue crack growth in various likely configurations, develop both diver interrogated or surface interrogated devices and the best means of transmitting signals from subsea sites to the surface. This should result in the development of devices which could be used offshore to give warning of crack formation or to monitor crack growth situations.

5. Title:

The application of hydrogen permeation measurements to the monitoring of marine structures.

Institution:

North Western Universities Consortium, Manchester.

Investigator(s):

Dr. R.A. Cottis/Corrosion and Protection Centre, UMIST; Dr. R.A. King/Corrosion and Protection Centre Industrial Services (CAPCIS), UMIST.

Overall Aims and Applications:

Hydrogen-induced effects are one of the main factors restricting the selection of higher strength steels for offshore structures. The objective of this project is to develop a fundamental understanding of the factors influencing the permeation of hydrogen through a steel membrane, and to correlate the hydrogen permeation rate with mechanical damage caused by the hydrogen. A long-term objective of the proposed work is to provide a basis for the use of hydrogen permeation measurements as a monitoring technique for hydrogen damage, thereby providing a tool for the better control of cathodic protection systems and inhibitor additions to oil and gas pipelines. Results will be of use to all offshore suppliers, contractors and operators.

6. Title:

Magnetic crack detection of surface defects at welded joints by Hall effect devices.

Institution:

North Western Universities Consortium, Manchester.

Investigator(s):

Professor F.M. Burdekin/Civil & Structural Engineering, UMIST.

Overall Aims and Applications:

Present techniques of magnetic crack detection can be time-consuming at the fabrication stage and inconclusive when applied under water, particularly when access is difficult. This project aims to improve on present methods of magnetic crack detection, both at the fabrication stage and inservice, by the use of Hall effect devices to provide an electric signal output from sensors which can be displayed, recorded and subsequently analysed thus overcoming the above problems. In addition to improved detectability of cracks, such devices may also provide an indication of depth, not given by present techniques. The results will be made available to industry.

7. Title:

Squid magnetometers for non-destructive testing.

Institution:

University of Strathclyde, Glasgow.

Investigator(s):

Dr. G.B. Donaldson/Applied Physics; Dr. G. Hayward/Electronic & Electrical Engineering.

Overall Aims and Applications:

This is a speculative and innovative program, designed to study the usefulness of SQUID (superconducting quantum interference device) magnetometers as detectors of the magnetic anomalies produced by surface-breaking cracks in ferrous structures. Using a novel low-field magnetisation technique and gradiometric pick-up coils of a new design, we expect to be able to utilise the outstanding sensitivity of SQUIDs (up to five orders of magnitude better than, say, flux-gate magnetometers) to greatly improve on present crack detection techniques. For example, we should improve both minimum detectable crack volumes and maximum allowable transducer stand-off (say to 10cm). Moreover, we expect the technique to work for structures immersed in sea-water.

Beyond this program, the long-term aim of this project is to develop a portable underwater crack-scanning magnetometer system, requiring only a small low-power magnetisation energy supply, which would eliminate the need for the removal of marine growth and other deposits before testing.

8. Title:

Evaluation and development of non-destructive testing techniques.

Institution:

LONDON CENTRE, University College, London.

Investigator(s):

Dr. R. Collins/Mechanical Engineering; Professor D.H. Michael/Mathematics.

Overall Aims and Applications:

A.C. Potential Difference techniques for NDT of offshore steel structures:

(i) To develop non-contacting probes and probes of significant loop area capable of measuring through surface fouling.

(ii) To investigate preliminary observations that ACPD readings are affected by residual stresses. Work is required to exploit the techniques as a practical method for measuring residual stress.

9. Title:

Non-destructive evaluation of marine structures, using ultrasonic techniques.

Institution:

LONDON CENTRE, University College, London.

Investigator(s):

Dr. L.J. Bond/Electronic & Electrical Engineering.

Overall Aims and Applications:

To improve existing ultrasonic inspection techniques and then to provide the theoretical understanding of wave propagation and scattering required for the development of new and quantitative techniques which will provide full defect characterisation and residual stress measurement, as required for fracture mechanics on steel structures. Computer models will be produced having application in understanding and overcoming a wide range of real NDT problems.

10. Title:

Electromagnetic detection of surface defects in marine installations.

Institution:

Brunel University, London.

Investigator(s):

Dr. J. Blitz/Physics.

Overall Aims and Applications:

Use of multi-frequency eddy currents to detect and examine surface defects in metal structures forming part of marine installations, and to resolve effects of changes in magnetic permeability, electrical conductivity, and lift-off, e.g. as occurring with welds. This should result in improvements in assessing the integrities of marine structures and should prove to be of particular value to organisations concerned with North Sea exploitation.

11. Title:

Nondestructive inspection of offshore structures by computerised scanning with gamma-photon counters.

Institution:

Brunel University, London.

Investigator(s):

Mr. B. Bridge/Physics.

Overall Aims and Applications:

Construction of prototype device for underwater NDT using ionising radiation but without film, built round 36" riser as test piece. Images computer reconstructed by scanning both through-transmitted and Compton backscattered radiation with array of high collection-efficiency gamma-photon counters. Relative merits of the two methods compared in the presence of simulated defects and marine growth. Performances compared with theoretical equations already developed by the investigator. The potential of the fibre optic links between scintillators and electronics evaluated. Potential attractions of the method: (i) doesn't require complete removal of marine growth; (ii) wide range of inspection speed versus minimum detectible size options, impossible with film (e.g. large defects detectible at rapid scanning speeds, small defects detectible by sacrificing speed); (iii) no underwater electronics (apart from electric motor) if fibre optic linkages are successful.

12. Title:

Ultrasonic arrays for flaw location and characterisation.

Institution:

University of Strathclyde, Glasgow.

Investigator(s):

Professor T.S. Durrani, Dr. G. Hayward, Dr. A. McNab/Electronic & Electrical Engineering.

Overall Aims and Applications:

Studies on 1-D arrays at Strathclyde have established their unique ability in locating structural defects without the need for mechanical scanning. The project is aimed at extending present work to the evaluation of these arrays for defect sizing and characterisation over a larger region of interest. The endpoint of the research effort would be the development of prototype hardware, involving state-of-the art instrumentation for accurate defect location and identification. When incorporated as a stand-alone inspection tool or part of an automated module, the system is aimed at producing more accurate and reliable inspection results with a minimum of operator dependence. As such, it will be widely acceptable to all offshore operators involved in inspection and maintenance.